NATIONAL RESEARCH COUNCIL

AMERICAN GEOPHYSICAL UNION
TRANSACTIONS OF 1941

PART II

TWENTY-SECOND ANNUAL MEETING
APRIL 30 TO MAY 3, 1941
WASHINGTON, D. C.

REPORTS AND PAPERS
GENERAL ASSEMBLIES AND
SECTIONS OF GEODESY, SEISMOLOGY, METEOROLOGY,
TERRESTRIAL MAGNETISM AND ELECTRICITY,
OCEANOGRAPHY, VOLCANOLOGY.
AND TECTONOPHYSICS

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INTRODUCTION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, and its Executive Committee is the Committee on Geophysics of the National Research Council. The objects of the Union are to promote the study of problems concerned with the figure and physics of the Earth, to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication. In the accomplishment of these objects, the Union is divided into Sections following the plan of organization of the International Union of Geodesy and Geophysics. There are now eight Sections, namely, (a) Geodesy, (b) Seismology, (c) Meteorology, (d) Terrestrial Magnetism and Electricity, (e) Oceanography, (f) Volcanology, (g) Hydrology, and (h) Tectonophysics. A Section of Geophysical Chemistry was discontinued May 31, 1924, as the International Union had failed to provide such a Section. The Section of Hydrology was established November 15, 1930--matters pertaining to scientific hydrology referred to the American Geophysical Union had been previously looked after by special committees on Hydrology. The Section of Tectonophysics was established April 9, 1940, for the purpose of promoting and encouraging research of fundamental importance to our knowledge of Earth-structure not covered in any one of the other Sections of the Union.

Annual assemblies of the Union and annual meetings of its Sections for the discussion of reports and for symposia are held each year. The first 13 assemblies and meetings--those in each of the years from 1920 to 1932--were held in Washington, D. C. Besides the annual general assemblies and meetings of each of the Sections held since 1933 in Washington, D. C., regional meetings of the Section of Hydrology were held at Berkeley, California (1933 and 1934), at Pasadena, California (1936), at Denver, Colorado (1937), at Spokane, Washington (1937), at Davis, California (1938), at Los Angeles, California (1938), at Spokane, Washington (1938), at Stanford University, California (1940), at Seattle, Washington (1940), and at Sacramento, California (1941). The transactions of annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bulletin No. 17; fourth, 1923, Bulletin No. 41; sixth, 1925, Bulletin No. 53; seventh, 1926, Bulletin No. 56; eighth, 1927, Bulletin No. 61; and ninth, 1928, Bulletin No. 68. Transactions of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June 1930, and those of the twelfth, thirteenth, fourteenth, fifteenth, sixteenth, seventeenth, eighteenth, nineteenth, twentieth, and twenty-first annual meetings were published in June 1931, June 1932, June 1933, June 1934, August 1935, July 1936, July 1937, August 1938, July and August 1939, and July and September 1940, respectively, in the series of miscellaneous publications of the National Research Council. The present volume, Part II of the "Transactions of 1941," also one of the miscellaneous publications of the Council, includes the proceedings of the twenty-second annual meetings held at Washington, D. C., April 30 to May 3, 1941, with the exception of those for the Section of Hydrology. [The proceedings of the regional meeting of the Section of Hydrology at Sacramento, California, January 16 to 18, 1941, including 42 papers and reports with considerable discussion, are published as Part I of the "Transactions of 1941."] At the first, third, and fifth annual meetings in 1920, 1922, and 1924, respectively, there were no scientific papers presented; therefore, the transactions for these were not printed but were mimeographed for limited distribution only.

The present volume (Part II) contains the 106 papers and reports, with discussions, presented at the twenty-second annual meetings of the Union and of all of its Sections held at Washington, D.C., in 1941 except for those of the Section of Hydrology, which are being published as Part III of the "Transactions of 1941." As in the "Transactions of 1940," the minutes of the General Assembly and of those of all the Sections, with their appendices, have been included at the end of Part II. The total attendance of members and guests at Washington was in excess of that registered, namely, 479--once more a satisfying gage of the service of the Union to geophysics in the United States. The attendance at the regional meetings continues to emphasize growing interest in the United States in the activities of the Union's Section of Hydrology and in snow-surveying.

Three resolutions were adopted at the General Assembly. These related to (1) more adequate meteorological bibliographic and abstract service, (2) radio time-signal service maintained by the United States Naval Observatory and Naval Communication Service, and (3) thanks for facilities extended to the twenty-second annual meeting of the Union.

There were two general assemblies of the Union, the first, devoted to the presidential address and the award of the William Bowie Medal, being held in Elihu Root Hall of the Carnegie Institution of Washington.

The third award of the William Bowie Medal, endowed and established March 1, 1939, for distinguished attainment and outstanding contribution to the advancement of cooperative research in fundamental geophysics, was made to Dr. J. A. Fleming at the General Assembly of April 30, 1941. Following the award of the William Bowie Medal, Professor R. M. Field delivered his retiring address as President of the American Geophysical Union on "Geophysics and world affairs: A plea for geoscience."

At the second General Assembly of the Union there was a symposium on dynamics of land-erosion. Six papers were presented in this symposium, these being followed by prepared discussions in most cases which increased the number of communications appearing in Part II of the "Transactions of 1941" by 13, thus making 19 the total number of communications as published herein.

At the meeting of the Section of Geodesy there were ten papers and reports presented, one bearing on the International Association of Geodesy, three on progress of geodetic surveys and methods, three on gravitational traverses and profiles, one on first-order leveling, and one on theoretical considerations of a determination of astronomical refraction from physical data.

As regards the Section of Seismology, the meeting was devoted to joint sessions between that Section and the Eastern Section of the Seismological Society of America. There were, in total, 23 papers and reports presented at the two sessions, these dealing with the international situation in seismology, seismology of the United States and Canada, seismological instruments, seismological records, and theoretical aspects of wave-propagation.

The Section of Meteorology heard ten papers, of which two dealt with measurements of ozone and condensation-nuclei, one related to the United States Weather Bureau's five-day weather-forecasting experiment, one related to instruments, and six dealt with various theoretical matters in meteorology.

Thirteen papers and progress-reports were presented before the meeting of the Section of Terrestrial Magnetism and Electricity. These dealt with various aspects of geomagnetism including reductions of observations to mean of year, determination of the depth of the Earth's magnetic crust as based on data for local magnetic anomalies, relations to the aurora, the Sun, the ionosphere, and cosmic radiation, the improvement of magnetographs, and a comparison of two sets of trans-continental magnetic data.

Seven papers and reports were presented before the meeting of the Section of Oceanography, three dealing with oceanographic work for the past year by Government bureaus, one on research within physical oceanography and submarine geology, one on the fine structure of the edge of the Gulf Stream, one on vertical humidity-gradient over the cold water of the San Juan Archipelago, and another dealing with theoretical considerations of internal-wave investigations in the North Atlantic.

At the two sessions of the Section of Volcanology, 11 papers were presented and discussed, these including three on geomagnetic, gravitational, and volcanic measurements of the volcanic areas of Guatemala, one on atmospheric oxygen and volcanic gases, one on the magnetite ores of New Jersey, two on intrusives near Bancroft, Ontario, and eastern Connecticut, one on obsidian flow, one on helium retentivities of minerals, one on effect of pressure on acidity and water solutions, and one on solubility, transport, and crystallization by means of a vapor-phase.

The Section of Tectonophysics, in the morning and afternoon sessions, heard and discussed 12 papers bearing on deformation of marble at high pressures, ice-deformation in the flow of glaciers, dynamic morphism, quantitative experiments on salt-dome models and geological implications, effects of compression and wetting on the thermal conductivity of rocks, radioactivity of rocks, the cooling of the Earth, remarks relative to the thermal history of the Earth, cyclic convection-currents, identification of crustal layers, wave-analysis and the mechanics of earthquakes, and tectonic processes now in action.

Five regular sessions were devoted to hearing numerous reports and papers by the Section of Hydrology, while a sixth meeting was given over to a round-table discussion on the relations between infiltration and runoff. All of these papers and reports, with discussions, are being prepared for publication as Part III of the "Transactions of 1941."

The General Secretary edited the manuscripts for publication after some preliminary editing by the secretaries of Sections. The cost of publication was met through allotment by the National Research Council for maintenance of the Union, annual dues of members of the Union, and contributions of money and of services from the Carnegie Institution of Washington, from the

University of Nevada, from members of the Union, and especially from hydrologists both members and non-members. Each of the authors, except for a few who could not be reached, revised a carbon of the master-copy from which the Transactions were printed. The final master-copy was prepared by J. J. Capello, W. E. Scott, and A. D. Singer, and was planographed by the Kirby Lithographic Company of Washington. Besides its obligation to authors, to members of committees, and to our colleagues in the Western Hemisphere, who contributed to the twenty-second annual meeting, the Union is indebted to W. C. Hendrix for preparing many drawings, of which the originals submitted were not suited for planographic reproduction, and for photographic work.

The present Transactions of the Union continue to give evidence that its activities are an ever-increasing factor, nationally and internationally, in the advancement of the Earth's sciences and the improved application of knowledge therefrom to human economy and welfare.

Jno. A. Fleming, General Secretary,
American Geophysical Union

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30—MAY 3, 1941

GENERAL ASSEMBLIES

(A) PRESIDENTIAL ADDRESS AND THIRD AWARD WILLIAM BOWIE MEDAL

(B) SYMPOSIUM ON DYNAMICS OF LAND-EROSION

WASHINGTON, D. C.

(A) APRIL 30, 1941
(B) MAY 2, 1941

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Presidential Address and Award of William Bowie Medal
Elihu Root Hall, Carnegie Institution of Washington
April 30, 1941, 8 P.M.

GEOPHYSICS AND WORLD AFFAIRS: A PLEA FOR GEOSCIENCE

R. M. Field, President

The International Union of Geodesy and Geophysics was founded in the hopeful year of 1919, when the scientists of the world, largely under Anglo-French leadership, had ceased their highly regimented and destructive efforts in the art of war, and had naturally returned to their constructive efforts in the art of peace, that is, so far as peace and justice may be acquired through the invention and production of new gadgets, the alleviation of physical disease, and the further elaboration of a highly mathematical and a mechanistic but none too natural philosophy. The American Geophysical Union was organized in 1919 to serve as the American Committee of the International Union, and also, through its Executive Committee, to serve as the Committee on Geophysics of the National Research Council. It is important, especially at this time, that we should appreciate both the national and international responsibilities of our Executive Committee; the difficulty and delicacy of these responsibilities being even more complicated in time of war by the fact that several of our officers are also employed by the Government of the United States. In 1920 membership in the American Geophysical Union numbered 56, five of whom were ex-officio, and it has steadily increased to 1327. Thus the American Geophysical Union is today primarily an American Society of Geophysicists whose Executive Committee officially represents American geophysics, both in this country and abroad. Like its international parent, the American Geophysical Union is made up of Sections or Associations representing Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Oceanography, and Volcanology, and the Section of Hydrology was added in 1930. In 1940, after much careful deliberation, a new Section of Tectonophysics was added, in spite of the fact that this Section does not exist in the International Union. This necessity for the eighth branch to the candlestick came through the increasing interest and accomplishments of those students of earth-science who were coordinating the experimental and observational data derived from the study of the deformation of the crust of the Earth, both as to cause and effect. Tectonophysics is of particular interest to the structural and economic geologist, and our new Section will serve a unique and useful purpose in encouraging and supporting experimental and theoretical investigations of the deformation of rocks and all closely related phenomena. This statement is well supported by the excellent program which the new Section has submitted for this meeting.

It was probably not in the minds of the originators of the International Union of Geodesy and Geophysics that the terminology of the original seven Sections duplicated existing national or international organizations or societies. According to H. D. Harradon, the first international conference on terrestrial magnetism was held at Cambridge, England, in 1845, during the meetings of the British Association for the Advancement of Science. An International Meteorological Committee was established in 1872 and restricted in 1921 as the International Meteorological Organization. There has always been close cooperation between the students of magnetism and the students of atmospheric electricity.

The study of volcanoes, their products and activities, had been carried on by geologists long before the word geophysics was used in its present sense. Indeed, as early as 1740, Jean Etienne Guettard, "the Father of all national geological surveys," had recognized volcanic rocks in the Puy de Dome district of Central France, far removed from any active volcanoes. Guettard's observations were of particular importance in the progress of geology, since it was he who, for the first time, proved that basalt was an igneous and not a sedimentary rock. Also, as a volcanologist he initiated the study of all igneous rocks, whether effusive or intrusive, and thus suggested the more comprehensive field of volcanology and its related subjects of mineralogy, petrology, and geochemistry. It is interesting to note that the Section of Volcanology of the American Geophysical Union is now, fortunately, more or less of a misnomer and that this Section is actively engaged in the study and promotion of all important igneous rock problems which require the methods and techniques of geochemistry and geophysics.

Special mention should be made of the Section of Seismology, for the study of earthquakes provided the earliest and perhaps the most important contribution to our knowledge of the interior of the Earth and the catastrophic phenomena of its crust.

Oceanography, according to some authorities, would include the study and description of everything that had to do with the oceans and under the oceans. Within the American Geophysical

Union, however, there has been the growing tendency to limit the field of oceanography to physical marine hydrology. The subject of suboceanic geology is the particular responsibility of the Special Committee on the Geophysical and Geological Study of Oceanic Basins which was created by the American Geophysical Union in 1933. Because of the excellent and original work of this Committee, especially in gravimetry, submarine seismology, and acoustics, its Chairman is now engaged in directing cooperative research carried on by the Woods Hole Oceanographic Institution and the United States Navy. In 1935 the American Geophysical Union created a cognate Committee on the Geophysical and Geological Study of Continents; and, finally, in 1939, completed the geophysical trinity by authorizing the Special Committee on Cosmic Terrestrial Relationships.

The success of these special committees was so appreciated by the International Union that it created an International Commission on Continental and Oceanic Structure at the Edinburgh meeting in 1936. The three American committees and the International Commission have played a unique and important rôle in the integration of geophysical and geological techniques to the benefit of both fundamental and applied science. The committees on the Geophysical and Geological Study of Oceanic Basins and of Continents have been especially aided in their labors by the Sections of Seismology, Geodesy, Oceanography, and Terrestrial Magnetism and Electricity. It also should be mentioned that these committees have been able to borrow important apparatus, initiate fellowships, and obtain grants, all in the name of the American Geophysical Union. These special committees have truly exemplified the charter of our Union, which is "to promote the study of problems concerned with the figure and physics of the Earth; to initiate and coordinate researches which depend upon international and national cooperation, and to provide for their scientific discussion and publication." This cooperation between the Sections and the special committees has definitely proved the value of the committees themselves whose primary function has been to initiate continental and oceanic projects and expeditions which, because of their peculiar and comprehensive nature, might not have been attempted, or even considered, by the individual Sections, if, indeed, by any other organization.

The continued growth of the American Geophysical Union, both as to membership and activities, has been greatly aided by the publication of its Transactions, which have steadily grown from an original modest publication of 57 pages to the last edition of 1151 pages. While our Union is particularly fortunate in the large number of members who have accepted active responsibility in its executive and administrative affairs, we are all deeply indebted to John A. Fleming for his kindly, careful, and devoted editing of our publication. Had it not been for his peculiar enthusiasm and zeal, our Transactions would certainly not be what they are today. His has been a true labor of love, which we all feel should be recognized in a substantial way as soon as possible. There is probably no other scientific organization in the world which has produced such an annual publication, both as to quantity and quality, on such a small cash basis. Let us be selfish and wonder what would happen to our Transactions if anything happened to Fleming. Then let us be at least a wee bit sentimental, and assume that nothing that his colleagues could do would please him more than to insure the continuous production of the Transactions, so far as such insurance can be assured during these troublous times. Finally, let us be practical, and raise a sufficient fund to insure the future of our Transactions.

Three years ago a number of William Bowie's friends and colleagues endowed, designed, and created a medal in his name. This medal was accepted by the American Geophysical Union, and was awarded to the third recipient this evening. This medal is awarded only for outstanding cooperation in geophysical research, and not primarily for personal research, no matter how excellent such personal research may be. Indeed, the specific ideal of this award is that of the instigation and production of coordinated research on fundamental problems which could not normally be solved in any other way. Such activity is particularly appreciated in the American Geophysical Union whose usefulness, as an executive rather than as an honorary society, is primarily determined by the necessary coordination of the several branches of earth-physics in the common investigation of the Earth, its hydrosphere, and its atmosphere.

During the past eight years the Union, both officially and unofficially, has increasingly cooperated with other organizations, private, State, and Federal, in conferences, expeditions, and symposia. Notable among these activities have been our joint geophysical expeditions with the United States Navy and the United States Coast and Geodetic Survey, and our joint symposia on geophysics with the American Philosophical Society, the American Association for the Advancement of Science, and the American Institute of Mining Engineers. The Division of Physical Sciences of the National Research Council has cooperated with our Union, most effectively, in an important series of publications on the "Physics of the Earth," and also in the preparation of numerous bulletins on geophysical instruments, methods, and techniques. The Section of Hydrology has sponsored many regional meetings which have been so successful that the Executive Committee of the Union has recommended to the officers of the several other Sections the consideration of whether such regional meetings, as units or jointly with other Sections, might not be profitable and helpful in advancing the various research fields of geophysics. Several of the officers and members of the Union have also officially taken an active part in conferences and discussions with special committees on Education in Geophysics, representing the American Association of Petroleum Geologists, the American Institute of Mining Engineers, numerous colleges and engineering schools, and the National Roster.

The National Roster, as an important asset in national defense, is also related to the international aspects of geophysics. It is interesting to note that the plan of the personnel sheet on geophysics is particularly complimentary to the American Geophysical Union, in that it deliberately copies the subdivisions of geophysics as defined by our organization. This is far too complimentary to be practical, and it is indeed unfortunate that the earth-sciences, including geology, were not properly integrated in the light of modern practice. This whole matter touches so closely upon the relation of education to geophysics and earth-science that it should be reviewed at the earliest moment with the greatest of care by both the Division of Geology and Geography of the National Research Council and our Union. It has now been demonstrated nationally that there is not the proper interdepartmental cooperation between engineering, physics, and the earth-sciences in most of our educational institutions for the benefit of even a reasonably modern curriculum in the study of the Earth. Our American students, both elementary and advanced, are still seriously handicapped in their desire to enter the important, fascinating, and precise field of geophysics, as well as the applied phase of geodesy and geophysics which may be termed engineering geology. It is hoped that the Division of Physical Sciences of the National Research Council will become better acquainted with the data already available on this subject, and that both its chairman and its executive committee will, in the future, give more serious consideration to its national educational responsibilities, especially in relation to geophysics and geology. The National Research Council is particularly fortunate in its present chairman of the Division of Geology and Geography, who is intimately fitted to cooperate with the American Committee on Geophysics in the best interests of earth-science.

Perhaps the outstanding event in the history of the American Geophysical Union occurred in September, 1939, when it served as cohost with the Department of State for the Seventh General Assembly of the International Union of Geodesy and Geophysics in Washington, D. C. For several weeks previous to this, events in western Europe had rapidly become more disturbing. Delegates from most of the adhering countries (then 32 in number and including all of the present belligerents) arrived in fair numbers, but there was some discussion as to the advisability of cancelling the meeting. Finally, just previous to the meeting, Germany invaded Poland, and there was a hurried meeting of the Bureau of the Union which determined to carry on, in spite of the fact that the General Secretary, Brigadier Winterbotham, and several of the British and French delegates were called home. In making this decision the American Committee and the Bureau of the International Union were greatly encouraged and aided by the Department of State. From then until now the world has been progressively drifting toward a geowar, in which geophysics is playing an increasingly important part at sea, on the land, and in the air.

In his address at the opening Assembly, September 6, 1939, the President of the National Academy made the following statement: "While your cooperative efforts and your sessions may be somewhat handicapped by the lack of political understanding which now manifests itself between nations, you are, relatively speaking, fortunate in another regard. So far as I can see, you are unembarrassed in your deliberations by the hoard of economic and socialogical quandaries which at the moment beset the applied scientist either when he looks backward to contemplate his past achievements or forward in an attempt to plan the constructive contributions to the future" [see 1 of "References" at end of paper]. So speaks the engineer who, through the direct application of science, has so helped to increase the complexity of man's environment that he (the engineer) is giving some consideration to "an attempt to plan the constructive contributions to the future." It is not strictly true, however, that the scientist is not--even relatively speaking--"unembarrassed in his deliberations by the hoard of economic and socialogical quandaries which beset the applied scientist." In the first place, there is little, if any, distinction today between fundamental and applied science. This is certainly true of geophysics. Second, a large number of our scientists are necessarily employed by great chemical and engineering corporations and by the army and by the navy. Those who are not so employed, may be not only embarrassed but dismayed at that definition of science which is restricted primarily to astronomy, mathematics, physics, chemistry, and biology, and appears to pay no consideration whatever to the fundamental science of the Earth--to geoscience and georesearch in its relation to geoeconomics and to geopolitics--in short, to geography in the fullest sense of the word. Our American definition of science tends to become too selfish, too hard, and too glittering, too closely associated with gadgets, advertising, the installment plan, or merely the advancement of science.

Just previous to our Washington Assembly of the International Union, there was held an international congress of earth-science in another great country, but one which does not call itself a democracy. The slogan of this congress, displayed everywhere so that every Russian could read it in his own language, was as follows: "Science is called science just because it recognizes no fetishes and does not fear to raise its hand against everything that is obsolete and dying, and attentively listens to the voice of experience and practice" [2]. This definition of science, although it may not have been written by Joseph Stalin, was at least signed by him!

Science, democracy, human rights, freedom, and justice, why bother to define them? Because the present dilemma of the democracies is largely due to the fact that the very antithesis of all that we hold dear has not only been most clearly defined, but put into practice with such scientific and engineering efficiency as first to amaze and then seriously to frighten us--frighten us to such an extent that some of us wonder if enough time is now left for that careful and painstaking judgment so necessary for strong and competent action. Under these hurried and chaotic conditions, both here and abroad, there are American scientists who believe that this is not the time to reexamine our definitions, our activities, and our philosophy; that science, in the fullest sense, can contribute nothing immediately to civilization except in doing all that it can to help win the war--at least so far as the war can be won. This attitude of mind fails to recognize the present weaknesses of democracy in its hour of trial. It fails to recognize its duty, both in act and education, to that form of society under which scientists have flourished prodigiously for so many years. How many of us remember the particular compliment which our Secretary of State paid to the assembled geophysicists that September evening in 1939, when he said: "It is my fervent hope, which the people of this country share, that the day may soon come when the statesmen of the world will take a leaf from the book of the scientists and solve international political problems in the same dignified and friendly spirit." Exemplification of the discipline of "dignity and friendliness" during intense competition in cooperative research is the greatest contribution scientists can make to the growth of democracy.

During the last two years scientists have said much and written much concerning their rights and freedoms, but little indeed concerning their responsibilities and competence. Those who specify themselves as humanitarians have constantly referred to scientists as materialists with little or no conception of the truths of philosophy, religion, or democracy. The literature on such subjects has been quite without dignity and friendliness, and of a quality to corrupt good temper and good manners. This has been particularly true in many of our educational institutions. In his excellent article on "Education for democracy" the eminent biologist, teacher, administrator, and philosopher, Edward Grant Conklin, as late as 1939, wrote as follows: "It is amazing and pathetic to see so many teachers asserting that their one subject of study is the *sine qua non* of education. I have been through both the classical and the scientific courses of study, and ... I think I can appreciate the particular value of each of these subjects, but I have never been able to appreciate the point of view of those pedants who were forever denouncing subjects of study about which they knew nothing at first hand. Think of the words and tempers that have been wasted, and worst of all the education of students that has been sacrificed, in the war of the classics upon the sciences or of the humanities on both! As if the aim of education were information on some particular subject rather than the formation of habits and character" [3].

Professor Adler, in his paper on "God and the professors," states that "science contributes nothing whatsoever to the understanding of Democracy" [4]. To this the engineer, Philip W. Henry, quietly replies: "It is interesting to observe how democracy the past hundred years has expanded almost parallel with the expansion of industry under the guidance of science, which has provided mechanical slaves to do the bidding of mankind" [5]. Most Americans believe that science and democracy have been, and will continue to be, natural allies in the constant fight against tyranny and injustice, as well as in the promotion of the material welfare of man. This necessary cooperation of science and government may be effected either by compulsion and dictatorship, or by persuasion and leadership. It must not be forgotten, however, that intellectual leadership is needed in either case, and that individual education and individual competence are particularly essential to a true democracy.

On December 29, 1940, the American Association for the Advancement of Science held a symposium on "Organized science and democracy." The subjects discussed were: "In what ways has organized science helped to further democracy"; "In what ways has organized science hindered the development of democracy"; "Practical steps to improve the contributions of science to democracy" "Problems in the development of an effective program furthering democracy." The invitation stated that "organized science, as represented by the American Association for the Advancement of Science, is vitally concerned with the attacks on democracy." On December 31, 1940, the Council of the American Association for the Advancement of Science passed the "Charter-of-Democracy" resolution, which reads as follows:

"WHEREAS, At this time of international stress the American Association for the Advancement of Science, at its one hundred and sixth meeting convening in Philadelphia, a city sacred to the foundation of our republic, realizing the share of responsibility of scientific men for the general welfare of free peoples, seeks the cooperation of their English-speaking colleagues:

"BE IT RESOLVED, That the American Association for the Advancement of Science wants the cooperation of the British Association for the Advancement of Science in attempting to formulate, upon scientific principles, an international charter of democracy.

"BE IT ALSO RESOLVED, That a copy of this resolution be immediately sent (cabled) to the British Association for the Advancement of Science; and to all presidents of the affiliated societies of this Association, and sent to the editor of Science for publication."

This resolution was cabled to the British Association on New Year's day, and the following reply was received by cable from the British on January 8: "Await with interest your proposal concerning the international charter." On January 21 the British Association cabled again, as follows: "Further our cablegram, please inform whether you are sending proposals or awaiting ours," and the confirming letter received on January 28 included this further statement from the British Association: "It need scarcely be said that the President and general officers regard the subject of your Council's resolution as of the highest importance; they deeply appreciate the spirit of collaboration which has prompted you to send it to us, and they are carefully considering what steps can best be taken to reciprocate." Sir Richard Gregory has submitted a preliminary charter to his organization, and it will be considered by a special committee. This is to date the official history of the actions of the two largest, most representative, and democratic organizations of scientific men [6]. In no other countries than in the United States and Great Britain is there such a splendid opportunity for organized science to make its contributions to democracy, now and in the future. But the American scientists must bear the full burden of their responsibility while their British colleagues are being bombed.

As one of the originators of the "Resolution," I was asked to draw up a Preamble for a Charter of Democracy on scientific principles, with the advice of a number of American scientists. After some two months of travel, consultation, and correspondence, the following definition of democracy was sent to the Secretary of the American Association for the Advancement of Science for action by the Executive Committee on April 16:

PREAMBLE FOR A CHARTER OF DEMOCRACY AND INTERNATIONAL FRAMEWORK FOR A DEMOCRATIC WORLD ORDER

"Democracy is dedicated to the maintenance and advancement of 'Government of the People, by the People, and for the People.'

"Democracy can only be achieved by a spirit, a way of life, and a system of government in which the gain-seeking instinct, however important, must always and everywhere be subordinate to the desire for human service.

"Democracy aims to displace injustice and oppression for justice and mutual helpfulness, and to displace war and disorder for equal justice-under-law.

"Democracy demands an ever-increasing opportunity to learn, to labor, and to share the fruits of learning and labor among all men--coupled with the voluntary acceptance by each individual of the full opportunities, responsibilities, and disciplines of citizenship in a self-governing group.

"And the constant effort of Democracy, by act and education, must be to create a competent world order within which all nations and all peoples can be, and will be, assured equal opportunity in the quest for life and liberty, and in the pursuit of happiness."

The British Association is, for its part, attempting to define "a democratic charter of science." The first principle to be laid down will be that the fellowship of the commonwealth of science has "service to all mankind as its highest aim and the whole world as its outlook." This message seems to me to be quite as humanistic as it is scientific. Do you remember the words which Robert E. Sherwood in his play, "There shall be no night," put into the mouth of his hero, Dr. Carrel: "For the first time in history, a crumbling civilization is capable of discerning the causes of its decay. For the first time it has at its disposal the gigantic strength of science. Will we utilize this knowledge and this power? That's a question far more important than speculation about the possible results of the Munich crisis. In fact, behind this question are the real causes of all the problems we now must face." Thus Carrel refers to science and history. But was it not that great poet and wit, Heinrich Heine, who said a hundred years ago "that we learn from history that we do not learn from history." John Dewey, in his thoughtful treatise on "The scientific method and study of processes," says this: "One of the only two articles that remain in my creed of life is that the future of our civilization depends upon the widening spread and deepening hold of the scientific habit of mind: and that the problem of problems in our education is therefore to discover how to mature and make effective this scientific habit. Mankind so far has been ruled by things and by words, not by thought ... . Scientific method is not just a method which has been found profitable to pursue in this or that abstruse subject for purely technical reasons. It represents the only method of thinking that has proved fruitful in any subject ... that is what we mean when we call it scientific."

Among the duties of an executive officer of the American Committee on Geophysics one is to serve as a member ex-officio on several joint committees of the National Research Council. One of these is the Executive Committee of the Division of Foreign Relations. So far as I know, this Committee has never been encouraged to deliberate as a body on the increasing importance and difficulties of foreign relations, although it has met and listened attentively to the admirably worded report of its Chairman, who is also Foreign Secretary of the National Academy of Sciences. It would certainly seem as if the Division of Foreign Relations of the National Research Council could, under our democratic form of government, perform a greater service, both to science and to our country, than it is doing at the present time, especially as its members include executive officers of the American Association for the Advancement of Science, the American Academy of Arts and Sciences, the American Philosophical Society, the Department of State, and the International Unions of Astronomy, Biological Sciences, Geophysics, Chemistry, Pure and Applied Physics, Science and Social Relations, and several others. In times of peace, it has been assumed that the Division of Foreign Relations was chiefly concerned with the interrelation, if any, of the National Research Council and internationally organized science, but recently geoscience has become restricted to fewer and fewer countries until, at the present moment, its administration is almost entirely confined to the United States. Other divisions of the National Research Council, notably those of Geology and Geography, Medical Sciences, and Biology and Agriculture, have necessarily had foreign relations, both in Canada, Europe, and South America. But the research on foreign relations of these divisions, together with those of the Executive Board, have never been properly discussed or coordinated through the Division of Foreign Relations for the benefit of our government. This is notably true in our relations with Latin America at the present time. These remarks are naturally formulated on the democratic principle that committees representing a free organized science, so long as they are competent, are not displaced or rendered obsolete by parallel and independent action of the parent body.

Last spring, at the request of the Chairman of the National Research Council, I read the reports of the Committee on Science and Its Social Relations, which were prepared for the International Council of Scientific Unions. Copies of these reports were received by our National Research Council in February, 1940, and, therefore, constitute the last official international pronouncement on the subject. The report from Great Britain was drawn up by a Committee of the Royal Society of London, in consultation with our geophysical colleague, Professor S. Chapman. This report is a model of committee work in the serious and careful way in which it has answered the important but difficult questions posed in the questionnaire submitted by the International Committee, and transmitted by its Secretary to all countries adhering to the Union.

I would like, however, to refer particularly to excerpts from the reports submitted by Latvia and Estonia, and to quote directly from that portion of the Latvian report which deals with "science in our general world picture," as presented by Dr. Bružs.

"It seems that the daily press is the main channel by which scientific discoveries penetrate into the world picture of broad masses in our country. This channel seems to have a selective permeability for that part of scientific activity which has the taste of novelty and the label of unprecedented success. Newspapers are being widely read and a rich but totally uncritical mixture of poetical aspirations with pseudo-scientific revelations is being achieved. The creative and critical minds are doomed to personal isolation.

"Casual people rise out of this chaos with a belief that they have succeeded in obtaining a systematic plan of the world. They generally claim universality for this plan and likewise fix the limited truths of science with abundant personal imagination. Scientific material is serving uncontrollable purposes. I have three types of actual books on the world picture in mind; one type serves political ambitions and is a 'scientific' apology of a political platform, one serves personal professional ambitions, and the third serves the apologetics of the Church. Typical for these works is the utilization of famous scientific notions ('Wärmetod' of thermodynamics, 'limited world' of Einstein, Darwinian principles), unscrupulously neglecting the limits imposed on these notions by their authors.

"I distinguish two elements in science: Its utility and its intellectual charm. I do further believe that the latter is seriously endangered by the hypertrophy of the former. The reason for this lies in the fact that in modern civilization the utility element is 'naturally selected' by constant large-scale applications of experimental methods; the rudimentary intellectual element, on the other hand, is left to individual cultivation and the largest masses

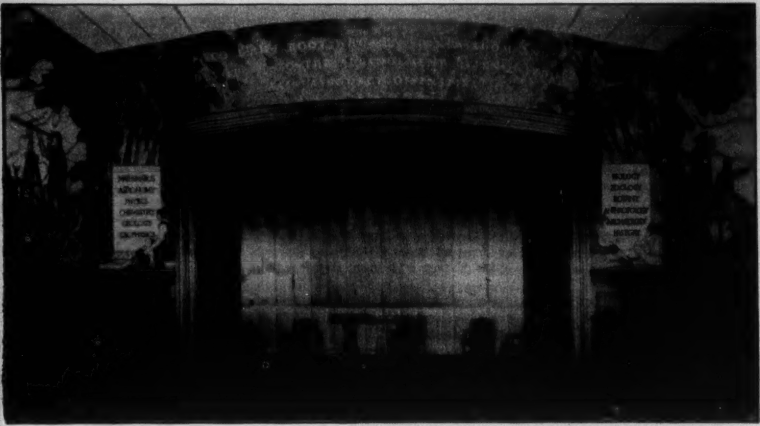

Fig. 1--Elihu Root Hall, Carnegie Institution of Washington

of population are supplied with cheap and tendential pseudo-scientific substitutes by the periodic press. I believe that this state of affairs is increasingly building up in the scientific periodic press as well, and can not be remedied without the creation of an arbitrative institute giving and periodically publishing its judicial advice. The 'Court of Science' should guard the intellectual treasures of science from pollution and drowning in the great body of pseudo-science and should have the right to punish wrong statements and misuse of scientific commission (professorship, editorship of scientific publications), and to recommend and filter off good work of today and of yesterday."

We, in this country, may feel that our "Court of Science" is composed of a number of institutions, such as the National Academy, the American Philosophical Society, the Carnegie Institution, the National Research Council, and the American Association for the Advancement of Science. Several of our newspapers and magazines are represented by excellent science editors who have and are doing their best to keep the public informed, both as to fundamental and applied activities of scientists and organized science. It would be interesting, however, to confer more frequently with our colleagues of the American press regarding the vital problems of publicity and education. Too frequently, these contacts are instigated primarily for the purpose of publicity, and the usual stereotyped and hurried "interviews" during the meetings of organized science are not conducive to that degree of "dignity and friendliness" which we should accord the "gentlemen of the press" who are equally concerned in the best interests of the public.

My plea this evening is for geoscience as an active partner with geoeconomics and geopolitics in the great human business of world affairs. In this beautiful auditorium dedicated by a great institution of science to the memory of a great statesman--"whose vision, wisdom, and devotion to the advancement of knowledge remain a source of inspiration"--are two tablets on which are inscribed the great divisions or departments of research and education, in their stratigraphic order (see Fig. 1). The tablet on my left lists the six major divisions of bioscience, culminating, through archaeology, in history. The tablet on my right lists the six great divisions of physical science, culminating, through geology, in geophysics. Agree or disagree with these divisions or their arrangement--here they stand for man's consideration. All have evolved by and through the activity of man. All continue to release great forces, great sources of intellectual and material energy which are used by man, and all are contributory to man's understanding of himself and of his environment. Thus, primarily by science, through engineering, has man developed the complexity of his environment, until geoscience in its philosophical, fundamental, and applied attributes has become the controlling force in the life of man and in the interrelations of masses of men.

This geowar is not merely the destruction of life and property, it is the destruction of sanity and reason. This geowar is not merely a problem in idealogies and theologies, it is a problem in geoscience. This geowar is not merely a battle of commentators and politicians, it is a battle in geoscience. We English-speaking people and our allies do not agree with the Axis powers in their limited, and, therefore, largely destructive use of science and engineering in world affairs, no matter how compelling may have been their immediate necessities. We believe that science through war is not normally sensible or competent. We believe that science may be better administered for the benefit of humanity, and that the scientist must help in this administration; for, in an intelligent society, he who creates is particularly responsible for what he creates. It has been said "the scientist should not be blamed for the use to which the world puts his brain-children, no more than a mother of a soldier should be taken to task" [7]. It might also be said that science (rather than necessity) is the mother of invention, and is naturally interested in the career of her progeny.

This difficult question of the competence and responsibility of scientists in world affairs can only be solved through the unselfish cooperation of the individual experts implemented by a free organized science composed of "companions in zealous research." Organized science must take its part in world affairs, without fear and without prejudice.

The enlistment of men of science in the cause of geoscience presents many serious difficulties. Scientists can not be drafted for this purpose, they must enlist of their own free will, aided by the ideals of those particular individuals and institutions which they respect and revere. They can not refer entirely to mass opinion because they are partly responsible for mass opinion. Under a properly educated democracy, however, they can always rely upon the normal intelligence and sympathy of the majority of those they seek to serve. No plan for the organization of men of science for the benefit of world affairs can succeed unless it recognizes the fact that the average scientist is at least as human as the average humanist; and that organized science, as do all great organizations, requires the cooperative skills of all manner of men. One of the outstanding attributes of science is that it has grown through specialization, but as specialization increases there is the corresponding danger of decrease of cooperation of the units or parts. The prime function of organized science is to stimulate cooperation.

From time to time, our American political leaders criticize scientific men for their failure to notice or take part in correcting the evils of unemployment, the evils of over or under production, the evils of undistributed goods, and other important practical matters. They also state, as does Joseph Stalin, that science should "attentively listen to the voice of experience and practice." The answer to this criticism seems to be that both scientists and legislators have not yet fully appreciated the fact that, under a true democracy, intelligent and competent action can only be achieved by unselfish and competitive cooperation of the greatest number of skills, and that in the practice and in the application of science the scientist is the staff man or adviser to the engineer or line worker [8]. Science promotes engineering and engineering promotes science, and both are completely dependent upon their services to humanity. The scientist will not shirk his responsibility to geoscience if he adheres to such a charter as that of the Carnegie Institution of Washington which is "to encourage in the broadest and most liberal manner investigations, research, and discovery, and the application of knowledge to the improvement of mankind." The engineer will not shirk his responsibility to geoscience if he adheres to the definition on the walls of the national headquarters of the engineering societies in New York: "Engineering is the art of directing men and controlling the forces and materials of nature for the benefit of the human race" [9].

Slowly but surely the relation of geoscience to world affairs is becoming more and more recognized by geoeconomists and geopoliticians, as well as by geophysicists and engineers. As one of many examples, I quote from an excellent report of the Committee on Tariff of the National Association of Manufacturers ["Tariff, international commerce and finance in a changing world"]:

"International commerce and finance trace back largely (1) to the uneven distribution of natural resources--fisheries and forests, metals and other minerals, deposits of other useful materials, and bases for agricultural production (such as soils, temperature, rainfall, the seasons, natural flora and fauna, etc.); (2) to the equally uneven development of the human race--both as to numerical strength and character of nationalities and individuals; and (3) to the lack of uniformity in the rise of the arts and sciences and in the utilization of the results of discovery and invention for the up-building of different regions and of different living standards within different nations.

"Largely because of this unequal distribution of resources, uneven development of human beings, and lack of uniformity in the rise of the arts and sciences and in the utilization of the results of discovery and inventions, there has grown up a world-wide trade in commodities between different regions and the people of different nations. This, together with travel and migrations of people and capital, led inevitably (a) to international relationships in the field of monetary materials, units and values, financial institutions, etc., and (b) to the necessity first for government supervision, and then regulation, of international travel migrations, investments, commerce, finance, and related problems" [10].

"Competition has led to the seizing of the best parts of the Earth by the most aggressive types of peoples and the extermination or expulsion of others to the less desirable places" [11]. From the dawn of history this method of conquest and colonization has led to the rise and fall of "master races" and imperial governments, equally aided and abetted by organized science and organized religion and organized trade. From the dawn of history man's reaction to the discovery of his physical environment has remained fundamentally the same; it is only the progressive intensity of this reaction which forms the basis of history. Much as we may wish it otherwise, the true history of the rise of civilization is the history of organized science in which, until quite recently, the most important facts were either unmentioned or misinterpreted by historians. That is why "we learn from history that we do not learn from history."

In 1933 it was predicted by the methods of geoscience that Japan would invade China via Manchukuo, and that Spain would be the preliminary battleground of the next European war [12]. Following the treaty of Versailles, it was predicted by geoscientists that the treaty would fail; that it was indefensible chiefly because its geoeconomics and geopolitics were not founded on geoscience. Because the statesmen of the world had not appreciated the fact that "A sane control of human conduct and relations must be based on a clear understanding of the true function of material things in human life" [13]. "Man's achievements in the physical sciences and in the arts of communication, transportation, and mechanized production, have led to the frequent assertion that he has conquered nature. This assertion is too sweeping. Civilization is not an enslavement of a constant and stable Earth. Man does not conquer the Earth but strives to enter into harmonious relationship with it ... In some instances nature's ways have been so modified by inadequately planned works of man that now engineering and economic experience indicate the need of readjustment in respect to many of these relations; in some aspects a more intelligent conformity to certain basic, inexorable conditions imposed by nature; in other aspects a more intelligent utilization of her generous gifts" [14].

The natural resources of the world are like moneys in the bank. They may be:

Hoarded without benefit to commerce; expended injudiciously, resulting in economic chaos; used to enrich a few at the expense of many; the primary cause of national and international strife.

Or they may be:

Developed for the benefit of commerce; distributed according to natural economic laws; considered, so far as possible, the heritage of all people; and used in such a way as to alleviate, if not abolish, national and international strife.

Upon the solution of these problems depends the spiritual as well as the material welfare of the people of the United States, and of all peoples [15].

Among the numerous private agencies and organizations which have recently appeared for the promotion of democracy, of particular prominence is Federal Union, Inc., which was formed in July, 1939, to further the accomplishment of "Union now" of the United States and the British Empire. The essential weakness in this attempt to accelerate the cooperative efforts of the English-speaking people is neither its aim nor its purpose; it is the weakness so consistently advertised by many of our pseudo-scientific writers and commentators--the refusal to recognize the fundamental causes of geowar, and particularly the kind of responsibilities which must necessarily be assumed by a "nucleus United States of the World." Federal Union tacitly assumes that such a "United States of the World," created for "mutual advantage" of the democracies (particularly the British Empire and the United States), would solve most of the problems of geopolitics now and in the future. Perhaps it would, but only by force--leading eventually to a treaty very similar to that of Versailles.

The Chairman of our Committee on the Geophysical and Geological Study of Continents, in his primer on the world distribution of natural resources, states that each United Nation's government would have to be large enough to cover an area which will provide supplies of all necessary materials; markets for all finished products; opportunities for employment of all available labor and opportunities for investment of all available capital; and that the people within each area must make such use of science and engineering as will enable growing populations to enjoy a steadily rising scale of living [16]. An admirable experiment which we are still attempting in the greatest of all human laboratories--the United States of America.

Of all the major divisions of geoscience, geophysics is the most directly related to world affairs. It has a great responsibility in helping to win the war of geoscience, and the greatest opportunity to help engineer an international framework for a democratic world order such as may keep the war won.

The American Geophysical Union, because of its charter, its membership, its national and international experience, has an exceptional opportunity to cooperate with American organized science in contributing to the growth and power of good government. Ours is a Union of most of the scientific methods and skills so essential to the solution of our own and world affairs. In our executive relation to our parent organization, let us remember that our responsibility is not merely the advancement of geophysics. Our chief responsibility is to be ready to advise when our advice is called for, and in this endeavor we must give and require that essential cooperation for which the National Research Council itself was created and is maintained. In our growth as an American Society of Geophysics, we must remember particularly our duties to the public and to education. And, finally, but most important of all, in our executive relation to world affairs, we must remember our responsibilities to all humanity in its hour of trial.

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Princeton University,
Princeton, New Jersey

THIRD AWARD OF THE WILLIAM BOWIE MEDAL

Just preceding the President's address the third award of the William Bowie Medal of the American Geophysical Union honoring unselfish cooperation in geophysical research was made to John A. Fleming. Chairman L. H. Adams of the Committee on the Award of the William Bowie Medal made the following citation:

"Mr. President: On behalf of the Committee on the Award of the William Bowie Medal, I have the honor to present to you as the duly nominated and elected recipient of the William Bowie Medal, Dr. John Adam Fleming, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.

"The Medal, according to the conditions under which it was established in 1939, is to be awarded for distinguished service in geophysics and outstanding contribution to the advancement of cooperative research in this field of science. Dr. Fleming fulfills these qualifications to an unusual degree. He has been an outstanding organizer and coordinator of geophysical research in America and has exerted great influence on the progress of such work in other parts of the world. He has been instrumental in establishing international magnetic standards through intercomparisons at a majority of the world's magnetic observatories, and has encouraged and supported the improvement of absolute standards by electromagnetic methods. He has also developed methods for magnetic surveys on land and sea, and has planned and directed the world magnetic survey by the Carnegie Institution of Washington. He has initiated new experimental approaches to the investigation of the Earth's magnetic and electric fields. These investigations, which have utilized the advances in nuclear physics and radiotelegraphy, have already revealed the intimate relations between ionospheric and solar and terrestrial magnetic phenomena. Dr. Fleming was largely responsible for the fruitful program of oceanographic research during the last cruise of the non-magnetic vessel Carnegie in 1928 and 1929.

"Since 1928, he has been editor and publisher of the international quarterly Journal of Terrestrial Magnetism and Atmospheric Electricity, the only organ devoted exclusively to these subjects, and one of great constructive influence in their investigation. He took a leading part in the successful organization and execution of the International Polar Year 1932-1933, and as an officer of various scientific bodies has taken an active part in other researches of international scope. As General Secretary of the American Geophysical Union for 16 years he has stimulated geophysics in many ways, especially through the editing and publication of the annual Transactions of that body. He also organized and edited 'Terrestrial magnetism and electricity,' an important volume of the Physics-of-the-Earth series published under the auspices of the National Research Council.

"As an investigator as well as an administrator, Dr. Fleming's record is impressive. He has investigated the relationships of the Earth's magnetic and electric fields and solar and cosmic phenomena, and has made studies of the secular variation of the Earth's magnetic field and its geologic implications. He has designed, for use on land and sea, numerous magnetic instruments that have proved of great value in the work of the Department of Terrestrial Magnetism and have been adopted by governmental organizations in other countries.

"With all his varied interests and duties, Dr. Fleming has regularly found time to take part in the affairs of numerous scientific societies. The list of American scientific societies in which he holds membership is an imposing one, and he is an honorary or corresponding member of many foreign societies. Some of his activities of geophysical interest not already mentioned are as follows: President, Association of Terrestrial Magnetism and Electricity, International Union of Geodesy and Geophysics; member, International Commission of Terrestrial Magnetism and Atmospheric Electricity, International Commission for Polar Year (1932-1933), and Executive Committee of International Council of Scientific Unions; and trustee of Woods Hole Oceanographic Institution.

"For his leadership in a field in which cooperation is peculiarly important, and for his eminence as a director and an investigator, Dr. Fleming stands high on the rolls of geophysics. Mr. President, it is with unusual pleasure that I present Dr. Fleming."

President Field then presented the Medal with the following statement: "Dr. Fleming, it is my privilege, representing the members of the Union, to present you with this Medal because of your outstanding unselfish cooperative research in geophysics and because we know that in this action we will be praised also by all your friends in other lands tonight."

The recipient replied as follows: "Mr. President, Dr. Adams, members of the Union, and friends: I deem it an especial honor and privilege to have received this Medal. As you all know, it is founded in honor of our beloved colleague, Dr. William Bowie, who for so many years played so important a part in the establishment and improvement and growth not only of our Union of Geodesy and Geophysics in America but also throughout the world. It is a double honor to have received a Medal which bears his name. Dr. Adams has laid me so bare before you I hardly know what to say. I think some of his remarks are hardly warranted, but I do assure you that I appreciate this honor deeply and I thank you from the bottom of my heart and thank those who have helped me to make it possible to do whatever I have done in geophysics."

SYMPOSIUM ON DYNAMICS OF LAND-EROSION

NATIONAL ACADEMY - RESEARCH COUNCIL BUILDING
2:30 P.M., MAY 2, 1941

GEOMORPHIC ASPECTS OF NORMAL AND ACCELERATED EROSION

C. F. Stewart Sharpe

Geologic norm of erosion--The twin concepts "normal erosion" and "accelerated erosion," commonly considered to include all erosion past and present, are disarmingly simple. If interpreted literally, they suggest that accelerated erosion was unknown before the coming of man, and, conversely, that the changes brought about by man merely quickened the pace of certain normal processes. Both of these interpretations are misleading.

Realizing that normal erosion was a flexible quantity varying widely with meteorological, tectonic, and other influences, Lowdermilk, in 1929, set up an idealized standard of natural erosion, aptly named the "geologic norm of erosion" [see 6 and 7 of "References" at end of paper]. Erosion was considered in the broadest possible sense and was made to include the mass-movement processes, many of which are highly effective in the natural denudation of the lands.

Transition from the geologic norm of erosion to present-day erosion has involved far more than simple acceleration. Extensive changes of balance in the effectiveness of mass-transport and mass-movement must have taken place. On the natural landscape, streams carved their channels much as they do today, but the percentage of permanently flowing streams was probably larger, and the percentage of ephemeral and intermittent drainages smaller, than now. There was generally a good plant-cover in humid lands and, so far as that covering was complete, slope-washing was prevented. The amount of soil-removal by slope-washing or sheet-erosion must have been small. Owing to good infiltration into deep mellow soils rich in humus, however, mass-movements of soil down slope by creep must have been highly effective. Streams received much of their load from creeping valley slopes, but because of an equable hydrologic regimen resulting from good ground-storage, streams carried their loads with relatively small fluctuations in transporting power.

Despite the rapid destruction brought on by clearing the lands for cultivation, it is evident that soil-erosion is not altogether a new process introduced by man. Very slow erosion of surface soil is an essential pedogenic process, and must have been active long before the first crude tillage of the soil. Under natural conditions, too, local and occasional events temporarily induced serious acceleration of soil-removal. Strokes of lightning in the dry fall forest, devastating blights, uprooting tornadoes, and sudden downpours of tropical cyclones all can penetrate the land's vegetal defense and expose the soil to accelerated erosion.

Interrelation of vegetal cover and soil-profile development--Protection by plant-cover retards the removal of surface soil and gives time for the soil-forming processes to work to completion. Without vegetation's aid to weathering and to the chemical and biological processes of soil-formation, mature soils could not develop. Together, mature soil and vegetation reduce runoff. Stems, roots, and plant-litter retard surface flow, and, from the leaves, moisture is returned to the air by transpiration.

Climate, working through its control of the plant-cover, produces great regional variations in mature soils. In humid and sub-humid lands, where the surface is normally well covered with vegetation and vegetal litter, deep soil-profiles can form. In regions too arid to have adequate plant-protection, gullying, sheet-washing, and wind-erosion have always been active. Without mantling vegetation, there can be no soil-material on slopes steeper than the angle of repose, and even on more gently sloping land the products of weathering wash or blow away almost as quickly as they are formed.

Changes in erosion brought about by man's use of the land--Normal soil-development, normal erosion, normal balance of the several processes of denudation, and even normal sculpturing of the surface of humid lands, then, can take place only with the presence of a normal vegetal cover. Man, by removing the natural vegetation, has destroyed the balance of all of these relations. In clearing the forests and baring the land for cultivation, man has added his destructive powers to those of nature. Runoff has been greatly increased, both in rate and amount and, as a result, streams now flow less regularly, their load is carried fitfully, and their floods reach higher crests.

Changes wrought by man have increased sheet-erosion, rilling, gullying, and wind-erosion. These processes truly have been accelerated. The natural downhill creep of the soil, however, now is of smaller relative consequence than under natural conditions. It is probably smaller in absolute value, too, owing to the general reduction in ground-moisture.

Recent work on geomorphology of accelerated erosion--Recent studies by the Climatic and Physiographic Division of the United States Soil Conservation Service have increased our knowledge, not only of the dynamics of accelerated erosion, but of the whole relationship of the present accelerated cutting to erosion in the past. Field-work in the Piedmont of South Carolina, for example, has helped to explain the rapid erosion of abandoned lands and has outlined the life-cycle of the characteristic deep, caving-walled, Piedmont gully.

On agricultural lands, the periodic reworking of the surface soil helps materially to prevent concentrated erosion. Soil is still removed by sheet-erosion and rilling, but listing and cultivating tend to equalize surface irregularities and prevent gully formation. When land is abandoned and this equalizing process ceases, rills persist and rapidly grow to gully size.

The direct results of rainfall and runoff in producing sheet-erosion in the Piedmont can readily be seen in micro-geomorphic forms, such as miniature soil-pillars capped by stones, leaves, twigs, or miscellaneous matter. Pillars almost four inches high, protected only by a tight covering of lichen, show strikingly the protection offered by even a thin layer of organic material.

As rills develop and deepen, stones left by the sheet-washing of the finer soil-components tend to migrate down the barren slopes and accumulate in the beds of the rills, forcing the channels to move laterally into less resistant material. Only exceptionally heavy rains can remove the stones from the smaller channels.

On the slopes between rills, frost and lesser daily temperature-changes loosen the surface layer of bare soil and prepare it for easy removal. Unpublished data from sloping test-plots show that by the action of needle-ice or spew-frost in one moderate freeze and thaw, more than 18 pounds of soil per 100 square feet of surface may be loosened and allowed to slide or fall to the base of the slope.

The thick fluffy crumb-mulch that forms on bare surfaces of the B-horizons on many of the Piedmont soils is found to offer protection against light rains, but is removed by heavier precipitation. Measurements of the loss of crumb-mulch from small gently sloping plots of Cecil, Davidson, Lockhart, and Georgeville soils show rapid removal directly correlated with the volume and intensity of rainfall. Iron markers 3/8 inch in diameter driven two feet into the ground on these plots reveal the carrying away of an average of 1/4 to 3/4 inch per year, with a maximum of more than two inches in as many months at individual markers. Other investigations of sheet-erosion and rilling are now in progress.

Where erosion goes unchecked, the pattern of small drainage-ways soon becomes better integrated, and the larger rills develop into gullies. The life-cycle of the Piedmont gully, underlain by a weak saprolite, or zone of rotten rock, has been traced through four stages by Ireland, Sharpe, and Eargle [4]. These gullies migrate headward up the channel, and several stages may be represented simultaneously in a single gully.

First is the stage of downcutting, when the gully is limited to the A- and B-horizons. Water-scour, loss of material from gully walls by frost-action, and washing down of crumb-mulch mark this stage. It ends with the development of pot-holes, penetrating into the saprolite. Although in some parts of the Piedmont the tight B-horizon type of material reaches to a depth of ten or more feet, and gullies can be large even in this stage, growth in stage one is relatively slow. This is the time to stop gullies!

Once cutting has penetrated the base of the B-horizon, marking the start of stage two, gully growth takes a tremendous spurt. Downward cutting gives way to rapid enlargement by a headward migrating knickpoint or overfall. This is the stage of fastest enlargement and maximum size and depth of gullies. Seeping of ground-water from the gully head, and back trickling of flow down the head wall beneath the protruding lip remove the weak material low on the gully wall, and caving of the resistant lip results.

Maximum rate of gully growth during this second stage depends on the alternation of two types of storms. Most of the caving of gully walls follows prolonged widespread storms of low intensity, the drizzling rains or "'tater soakers" usually associated with the passing of a warm front. This type of storm, characteristic of the winter months, tends to choke the gully channel. Side walls of gullies retreat, and may reach a low enough angle, so that stabilizing vegetation can gain a foothold. Thus, a gully generally shows its most benign aspect in the late winter and early spring, and this would be the optimum time to divert water, and undertake to establish vegetation on the walls.

Few of the drizzling winter rains cause much removal of material from the gully channel. That is done by the cold-front rain, characteristic of summer months, by summer thunder-showers, and by occasional tropical cyclones. Periodic observations of selected Piedmont gullies showed that material falling from gully walls in January lay almost undisturbed till well into the summer and, where caving had been especially heavy, the material was not completely removed for more than a year [4].

Following the rapid deepening of the gully in stage two, enlargement goes on much more slowly. If the gully channel is graded to a local base-level, the walls may in time slope back to a normal angle of repose. This is the third or healing stage and, where the cycle is complete, is followed by the final stage, stabilization, marked by the covering of the gully walls with vegetation, and in some places by the silting of the gully until it is partially or completely filled. Use of this knowledge of the gully-cycle in the planning of gully-control measures will make for economy of effort and provide more lasting results.

Basic research on the geomorphic background of soil-development and accelerated erosion in the Piedmont shows that the region has had a complex history of cutting and refilling. It has long been known that many of the Piedmont valleys contained feet, or even tens of feet, of fill, largely the result of deposition from overbank flooding. The common presence of a layer of peaty material, containing leaves, cones, and large logs, at a depth of 5 to 20 feet beneath apparently normal mature soils of upland hollows has only recently been recognized. Detailed investigations by Eargle, briefly reported in Science [2], included the boring of more than 800 auger holes and showed the existence of buried organic matter in many places where its presence had not been suspected.

Even the land form in which these deposits characteristically are found has received little attention in this country. It is described by German geomorphologists as the Delle [9] and gradually is becoming known here as the "dale" [8]. The typical dale is a broad rounded depression, the sides and bottom of which merge without any abrupt angle. Many dales are now cut by longitudinal gully channels, but they are believed to have been channelless under natural erosion-conditions. Analysis of the landscape of the Piedmont Upland shows that dales make up a large part of the area. In little-dissected sections, the surface of the dale may have a relief of only a few feet. Elsewhere the difference in elevation from bottom to rim may be 50 feet or more.

The large number of filled valleys and dales in the Piedmont indicates that at one time, during or before the Pleistocene, the surface of the land was much more rugged than it is now. Following this period of greater relief, the filling or partial filling of the valleys, accompanied by erosion and mass-movement of material from the hills and ridges, produced a much subdued topography. Immediately before the introduction of agriculture, the surface of the Piedmont was very gently undulating and broad low ridges alternated with deeply filled dales. Trenching by recent accelerated erosion has exposed in places the considerable depth of pre-agricultural fill.

The finding of deep fills in many areas of the Piedmont introduces complications into the mapping and interpretation of Piedmont soils. It has long been believed that the mature soils of the Piedmont are derived from underlying sedentary materials and that soil series correlate closely with specific rock types. Cecil soils, for example, are considered to be derived from a granite, granite gneiss, or crystalline schist parent rock. Soils with typical Cecil profile are now found to lie not only on sedentary materials of these types but on fills, which in turn may overlie an altogether different type of bedrock.

Sections constructed from series of borings across dales show that on the upper slopes of a dale the soil is usually relatively thin. A three-foot auger may be sufficient to reach saprolite. Farther down the slope, the layer of soil and soil-material is thicker, and in the center of the dale may approach 30 feet. The characteristic profile in the dale bottom shows mature soil with the B-horizon grading downward into a clayey B-like zone. Below this are several inches to several feet of peaty material, which in most places lie on a thin layer of quartz gravel, resting in turn on saprolite. From the distribution and texture of the deeper parts of these fills, it appears that both slope-washing and soil-creep have contributed to their formation. Some of the soil-material is definitely laminated and was deposited from flowing water. Other parts of the material are massive and appear to be the product of soil-creep.

On the side slopes of the dale, the organic layer normally is missing, but a layer of quartz fragments beneath the soil-material marks the line between undisturbed material below, which retains rock-structure, and moved material above, which does not. This line of rock-fragments or stones is one of the most important keys to the location of deep soil-masses. It was noticed as early as 1882 by Kerr [5], but few workers have followed his interpretation or paid much attention to the phenomenon since that time.

The significance of this irregular layer was recognized during field-work of the Soil Conservation Service in the Piedmont in 1936 and the term "stone-line" was applied to it [10, 11, 4]. Further studies have shown, more and more clearly, the importance of this line. Differences in erodibility of adjoining areas on the same soil-series in relatively similar topographic position have been explained for the first time when physiographers have been able to determine that, in the more easily eroded area the soil directly overlay the parent-rock material, whereas in the more resistant area the soil-mass was underlain by a stone-line, or stone-layer, indicating that lateral migration or transportation had taken place. Stone-lines are most apparent in regions of granitic or gneissic rock deeply weathered to a friable saprolite, but cut by quartz veins that resist weathering.

The applications of these Piedmont geomorphic studies to conservation work are fourfold. They give a more complete understanding of soil-genesis in the Piedmont, and explain the causes of some of the local differences in soil-erosion. Second, the regular arrangement of shallow and deep soils within a dale or within several dales in a small headwater drainage indicates the necessity of using a physiographic unit as the basis for erosion-control and conservation operations. The concept of the unit-drainage, the small headwater basin of the Piedmont streams, is being developed as an aid in the preparation of coordinated farm plans. Third, an understanding of the physiographic history of the region and a knowledge of the common presence of deep soils make it feasible to utilize the deepest soils for construction of waterways and other drainage-structures, thereby assuring against rapid cutting out in case of excessive storm-runoff, as might occur on a shallower soil underlain by deep saprolite. Appreciation of the physiographic pattern and history makes it possible to locate the deep soil-bodies of an area with less expenditure of time or effort. Fourth, the presence of former deep valleys indicates that accelerated erosion can take place without the aid of man, and that periods of excessive cutting can, by moderate change of conditions, be halted and replaced by periods of alluviation.

Evidence of former deeper erosion is by no means limited to the Piedmont. Unpublished studies by Ireland on the Caddo Canyon area of west-central Oklahoma show a great depth of fill of probable Tertiary age in old rock-cut canyons. Recutting of the canyons by removal of the fill has been going on since before the coming of agriculture to the area. Since 1914, one of these drainageways has been enlarged from a channel approximately ten feet deep, crossed by a small wooden bridge, to a canyon 55 feet deep that had to be bridged by a 75-foot steel truss. A number of canyons of this sort have already been reexcavated in Caddo and Canadian counties, and it is probable that they are part of a system that extends beneath a considerably larger area. The importance of preventing further uncovering of the old rock canyons is obvious.

Bryan [1], Hack [3], the Soil Conservation Service [12], and others have shown that in the valleys of the Southwest many channels have been cut and partly or completely refilled prior to the present acceleration of erosion. Regardless of their cause, these older alternations of cutting and filling show that in the Southwest, as in more humid parts of the country, the geologic norm was highly variable.

Conclusions--Filled channels in many parts of the country show that under natural conditions the land was far from free of local or occasional acceleration of erosion. The change from pre-settlement normal erosion to post-settlement conditions of accelerated erosion was, in part, an increase in the proportion of the land subject to accelerated erosion, in part an increase in the degree of acceleration, and in part a modification in the balance of the processes of erosion and denudation. On the veins of the leaflike normal drainage network, erosion was accelerated. On the intervein areas, there was a marked change in process, rather than simple acceleration. Mass-wastage by soil-creep, earth-flow, and other mass-movement processes gave way, in part, to the removal of the soil by slope-washing or sheet-erosion, which logically resulted in the development of rills and gullies.

Consciously or unconsciously, geomorphologists have always studied accelerated as well as normal erosion. Concentration on accelerated erosion, however, has opened a new and promising field of geomorphic research, in which results of considerable economic worth are being obtained. Only a beginning has been made, but already it is becoming plain that detailed studies of the dynamics and land forms of accelerated erosion will help to clarify principles of the geomorphology of normal erosion as well.

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LAND-EROSION--NORMAL AND ACCELERATED--IN THE SEMIARID WEST

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Successful control of erosion and floods requires an accurate problem analysis. It is essential, first, to know the relation of the current flood- and erosion-phenomena to the geologic norm and, secondly, to determine the relative importance of each of the many factors that contribute to the problem.

These considerations are especially important in the semiarid West where conditions of climate, topography, and the plant-and-soil mantle are highly varied and significantly influential in determining the character of erosion and runoff. Here, the norm in one drainage may mean imperceptible erosion and relatively uniform stream-flow. In an adjacent area the normal may be characterized by unstable slopes and channels and greatly fluctuating streams, frequently in flood-stage. Here, also, it is not uncommon for the degree of soil-stability and the regimen of stream-flow in one watershed to be due primarily to some dominant factor such as climate, topography, or condition of the plant-and-soil mantle, while in another the forces of several factors may compensate to establish a delicately balanced combination.

The factors which condition floods and erosion may be summarized in three broad groups: (A) Precipitation, amount and distribution; (B) basin and stream-channel characteristics; and (C) edaphic conditions, including soil-mantle and plant-cover. Precipitation, temperature, and gradients are always accepted as contributing causes, but the role of soil-and-plant mantle is too often ignored, exaggerated, or minimized.

Data derived from a wide range of experiments [see 1 of "References" at end of paper] and discriminative observations both in America and Europe show definitely that areas on which the tree, brush, or herbaceous cover has been undisturbed absorb water more rapidly, erode less, and contribute less surface-runoff than comparable areas on which the plant-and-soil mantle has been disturbed, that is, cleared, burned, or grazed.

The results of these investigations are of far-reaching importance in any problem analysis. If deterioration of plant-cover gives rise to accelerated runoff which causes floods, then downstream engineering structures may be able temporarily to confine the flood-flows and the debris, but they will not lessen flood-frequency and height, nor will they keep the soil on the slopes nor the silt out of stream-channels, reservoirs, canals, and harbors. On the other hand, if floods are normal and are caused primarily by storms and steep gradients, with the depletion of plant-cover playing a minor part or no part at all, then to attempt to develop a control-program based upon watershed management and plant-cover rehabilitation would be futile.

The geomorphological aspects of erosion and floods--Knowledge of infiltration-rates together with hydrometeorological data are essential in determining the relative importance of the several factors which contribute to erosion and floods, but because of the heterogeneity of physical conditions these data cannot always be translated into quantitative terms for an entire watershed. However, the interaction of both static and dynamic forces operating within a watershed are resolved in the land form and structures. If properly interpreted, these present a physiographic history that gives meaning to hydrologic and ecologic data.

The geomorphologic approach [2] to the analysis of flood- and erosion-problems uses the concepts and the procedures of both geologists and ecologists. Such an analysis is predicated upon the principle that the history of gradational processes is recorded in the land-profiles of the watershed, in the plant-and-soil mantle, and in the character and structure of the material transported and deposited by streams.

Changes in any of the physiographic features from normal [3] are usually discernible. If recognizable, these changes may make possible a direct comparison between current and normal gradational processes and may serve as a basis for determining the cause of changed conditions and the assignment of relative importance to the various causative factors.

Stabilized slopes--In order to understand what constitutes normal and accelerated erosion it is necessary to know how surface stability has developed on soil-covered slopes, even on very steep slopes, and what forces produced and maintained them. For several years the writer has measured slopes in the semiarid region including Utah and Idaho to determine the maximum angles at which they stand at rest with and without vegetative cover (Fig. 1). Non-vegetated talus material stood at gradients between 68 and 80 per cent, or an angle of about 36°. Vegetated slopes, on the other hand, underlain by fine-textured soils, but derived from the same parent material as the barren talus, stood at angles up to about 60° (173 per cent). Without the protection of vegetation, slopes of such fine material would not stand even at gradients as high as the coarse talus.

The only way the soil-mantle could have been formed and retained on these overly steep slopes during the steepening period, or held in place today against the force of gravity, impact of rain, freezing, thawing, and surface-runoff was through interdependent development of the plant-cover and soil-profile in which the plant-cover serves the dual purposes of binding the soil and maintaining a high rate of infiltration. Any land-surface having a soil-and-plant cover, regardless of its degree of slope, is a product of all of the elements of the weather. These include the heaviest and the lightest storms, drought and frost, and the effects of fire, rodents, game, and all other natural influences which have operated through the period of slope-formation. Such slopes, by reason of the binding effect and adequate infiltration-rates afforded by the vegetation, have existed in spite of the cyclic changes of the climate as well as extreme variations within these cycles. All vegetated slopes, in other words, are a manifestation of an adjustment between aggradational and degradational forces in which the plant-cover is the key to stability. Depletion of the vegetation reverses the gradational processes and accelerates soil-removal and runoff (Fig. 2).

A sudden increase in the rate of erosion is accelerated erosion and it is caused or accompanied by a speeding up of runoff from storms or snow-melt. Indicators of such acceleration of erosion occur as newly formed gully systems cut into a previously undisturbed soil-mantle, as dead or residual plants, or invading plant-species, as an erosion pavement, or as vestiges of an older soil-mantle.

We can classify watersheds according to the degree of stabilization of slopes, into three categories: (A) Those whose mantle-soils are fully stabilized by vegetation; (B) those whose

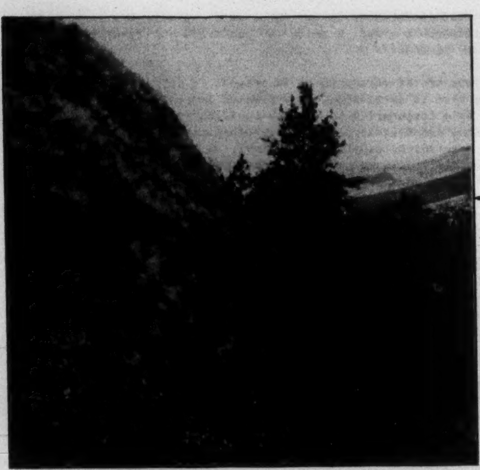


Fig. 1--Vegetated slopes underlain by fine-textured soils with well-developed profile are stabilized at angles far steeper than the angle of repose for unsupported earth materials [Here on the Clearwater Drainage, Idaho, a grass-soil mantle rests at angles up to 60° (173 per cent)]

Fig. 2--Balance between the aggradational and degradational forces has been broken on many watersheds of the semiarid West through impairment of plant-cover and disturbance of soil, resulting in accelerated runoff and soil-erosion (Here in the LaSal Mountains, Utah, the natural balance has been broken and erosion and runoff speeded up)

slopes have never been covered with a mantle-soil; and (C) those slopes whose mantle-soil has been so disturbed by impairment of vegetative cover that erosion of soil has been much accelerated.

Gradational history in stream-deposits--Runoff and erosion characteristics of these categories of watersheds are recorded in the deposits laid down by the streams. Texture and structure of deposits in fans and cones [4] indicate rates of gradation. Erosional products carried by streams from watersheds of stable, vegetated slopes are finer in texture, are richer in organic content, and are less in quantity than those from watersheds with high normal rates of erosion and runoff. After radical changes in rates of erosion and runoff take place in a watershed, streams discharge and lay down on their cones and in their valleys material significantly different in texture and quantity from that laid down previously. Stratification, humic horizons, erosional unconformity, and remnants of stream-terraces occurring in the valley fills also

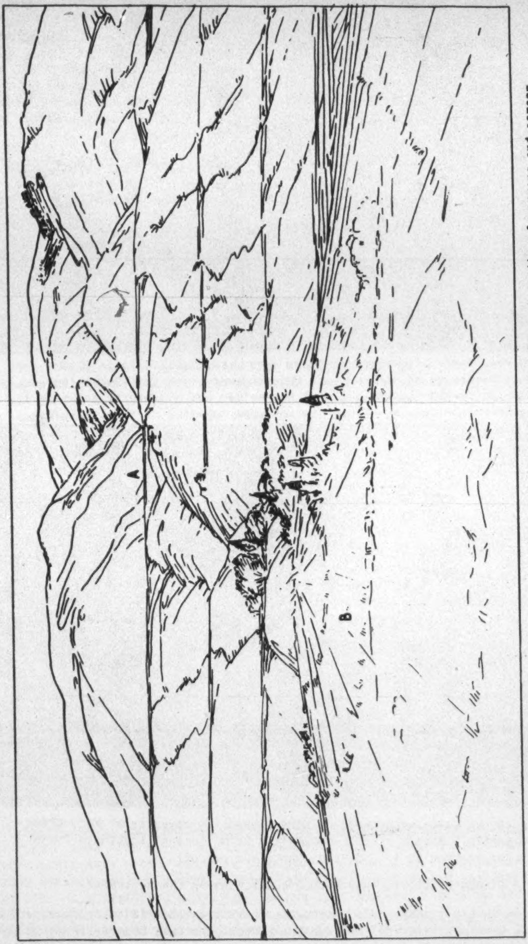


Fig. 3--Pleistocene Lake Bonneville left terraces, bars, spits, and deltas at mouths of canyons and across mountain front that makes possible the classification and comparison of materials laid down in pre-Bonneville, Bonneville, and post-Bonneville times [This drainage in northern Wasatch Mountains was barred off (A) at high stage of Lake and the bar has not been subsequently cut through; terraces on the pre-Bonneville cone (B) formed at recessional stages of Lake have not been obliterated by post-Bonneville erosion]

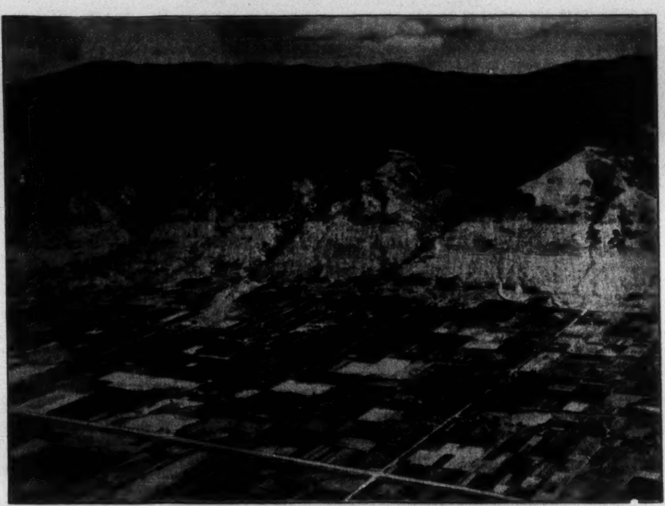


Fig. 4--Parrish Creek, Utah, discharged boulders onto the Bonneville Plain in 1930 for first time since recession of ancient lake thousands of years ago (Shore features, formed at different stages in level of Lake Bonneville and plainly marked base of mountains, together with deltas, enable one to judge normalcy of recent floods)

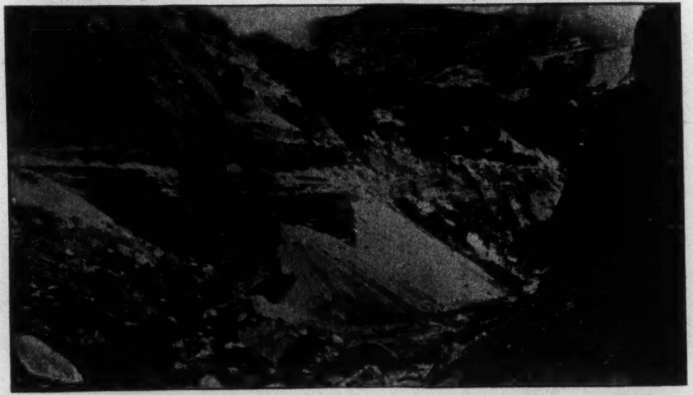


Fig. 5--Channelling during past two decades of Lake Bonneville deposits at Ford Creek Utah, has been clearly in excess of post-Bonneville norm (In some instances recent cutting has been deeper than in all previous post-lake period)

constitute a record of a stream's activity and record conditions on the watershed.

Post-Bonneville erosion and floods--Geomorphological investigations [5] along the west front of the Wasatch Mountains were most fruitful because the Pleistocene Lake Bonneville which once occupied the valley left deltas with distinct profiles at the mouths of canyons, terraces both wave-cut and wave-built (Fig. 3) across the land-features at the base of the mountains, and bars and spits athwart the drainages. These lake features make it possible to evaluate recent erosion in terms of normal for the post-Bonneville epoch. Also, materials transported from the watersheds and deposited at the mouths of the canyons can be classified as to time of origin, whether pre-Bonneville, Bonneville, or post-Bonneville, and comparisons can be made of the texture, structure, and quantity of these three age classes of material.

The amount of post-Bonneville erosion on the steep delta- and terrace-fronts at the base of the mountain has been slight. In their normal state these slopes are relatively smooth and graded with few gullies. On some drainages bars built across canyons in front of which occur pre-Bonneville alluvial cones of considerable proportions have not been cut through by post-Bonneville drainage nor have the marks of the receding lake left on the cones been erased. Since settlement in 1850, however, gullies have streaked the mountain front, and are becoming more numerous and deeper each year, following fire and excessive grazing. The wearing of trails and cutting of drag-roads up the slope has caused the concentration of runoff sufficient to cut gashes in the loose sands of the terraces. The surface-features of many terraces and deltas have changed more in the 90 years since settlement than in all the previous post-Bonneville period.

Floods also can be dated and compared. During the last two decades extraordinary floods, some of them viscous mud-rock flows, issued into the Bonneville Basin from a number of the short steep drainages between Salt Lake City and Willard, Utah (Fig. 4), destroying old established homes and depositing boulders, some weighing as much as 300 tons, and other debris on valuable property at the base of the mountains. These recent floods have cut to extraordinary new depths (Fig. 5) in the previously undisturbed sands and gravels of the deltas and terraces, and have deposited quantities and sizes of debris and sediment on the former bottom of the old lake greatly in excess of the post-Bonneville normal. Boulders weighing many tons (Fig. 6) came to rest on dark, humic soils, which, as revealed in well-logs, were formed from the fine silts and sands deposited in the ancient lake. The geological record shows current floods to be unprecedented in post-Bonneville history. Furthermore, some of these floods were the first to discharge boulders into the valley since the recession of the ancient lake thousands of years ago.

The slopes of these watersheds reveal conditions and changes that correlate well with the erosional and depositional history at the mouth of the canyons. The flood-runoff originated on relatively small areas (Fig. 7) at the heads of the drainage, whose soil-and-plant mantle had recently become depleted, even to the extent of denudation, by overgrazing, trampling, and fires. The total acreage of the areas of accelerated erosion make up only from five to ten per cent of the total drainage.

The flood-source areas are characterized by a recently developed gully system, disturbed soil-horizons, and remnants of the original plant-cover. Progressively outward from the eroded and barren areas, vegetal cover became more dense and gullies fewer and shallower until on well vegetated slopes there were no gullies or other indications of accelerated runoff.

While numerous freshly cut gullies testified to rapid runoff from the depleted "sore spots, there was no indication of accelerated runoff from adjacent and interspersed well-vegetated areas which unquestionably received the same amount of rainfall. From this evidence it was concluded that the formerly stable plant-and-soil mantle had been disturbed sufficiently to change the runoff and erosion relationships on these areas, giving rise to abnormal floods.

A further test of the validity of this interpretation of the character and causes of the accelerated erosion and runoff was provided by the application of preventive measures. Contour-trenches, check-dams, and artificial revegetation were installed on the flood-source areas to break up the newly formed gully system, reestablish base-levels of erosion, prevent surface-runoff, and to rehabilitate the plant-cover and improve the soil and soil-moisture conditions. These control-measures proved highly efficient in preventing the recurrence of disastrous floods during 1936 when measured storms of similar intensity caused mud-rock flows in comparable adjacent watersheds that had not been so treated.

Infiltration-tests and runoff-experiments on these flood-problem drainages further explain why flood-runoff came from small recently denuded areas, and why control was feasible. Eighty infiltration-tests made with a rainfall simulator (developed by the Department of Agriculture Flood-Survey Section and the National Hydrologic Laboratory) showed infiltration-rates of 3.43 inches per hour on undisturbed slopes as against 1.03 inches per hour on deteriorated slopes. Individual tests gave infiltration-rates on well-vegetated areas 12 times as high as on areas now devoid of plant-cover. Surface-runoff plots were established on areas representative of disturbed and undisturbed watershed conditions. The plant-cover density on the disturbed areas

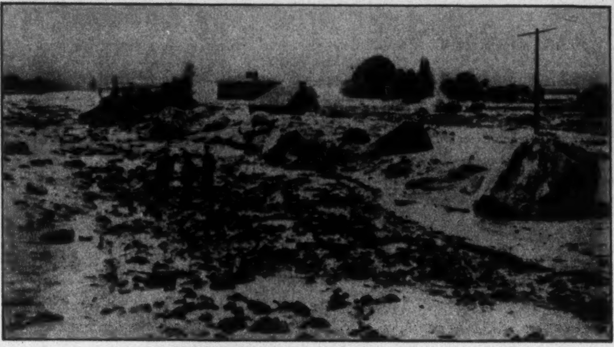


Fig. 6--At mouth of Parrish Creek in Utah floods in 1930 deposited flood-debris including boulders weighing many tons on rich agricultural lands whose soil has been formed directly from Bonneville sands and silts (Well-logs in this area show that similar floods had not occurred since Lake Bonneville receded from the area)

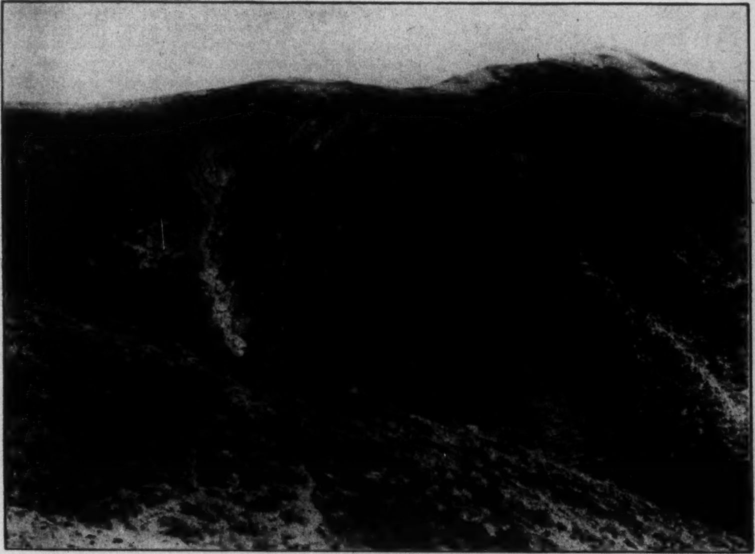
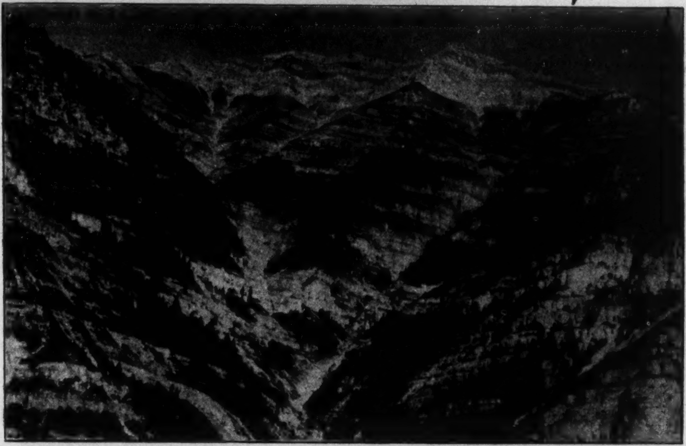


Fig. 7--Small areas on the flood-producing watersheds contribute runoff that accumulates into flood-flows (Infiltration-capacities have been greatly lessened by impairment of soil-and-plant mantle; with destruction of vegetation and development of a gully system, rainfall of only 0.47 inch is known to have produced boulder-laden floods)

was 2.9 per cent as compared to 14.3 per cent on the undisturbed areas. Runoff following four summer storms was equivalent to 0.24 per cent of rainfall on the undisturbed areas and 37.0 per cent on the disturbed areas. Disturbance of the plant-and-soil mantle resulted in 115 times more runoff.

Fig. 8--1936 flood-channel and deposits on Lost Creek Cone, Provo Canyon, Utah (Similar floods had occurred many times during post-Bonneville times, as is revealed by a study of form and structure of cone)

Fig. 9--Watersheds of Lost Creek (see Fig. 8) [Ground-conditions here correlate well with history of flooding as recorded in cone at mouth of canyon; 85 per cent of drainage-basin slopes are made up of barren rock; the small areas having well-developed soil-and-plant mantle are not eroded, nor do they give other evidence of accelerated runoff]



At the head of Parrish Creek at an elevation of 7,800 to 9,000 feet above sea-level, a watershed of 176 acres was selected for further study. This watershed was made up of both well-vegetated and badly impaired and eroded slopes. The flow from this watershed has contributed to several damaging floods since 1930, and, further, the geological evidence indicates that floods similar to those of the past 20 years had not previously occurred in post-Bonneville times. Eighty acres of the denuded area had been contour-trenched and reseeded. Eighty-one acres were well vegetated and approximately 15 acres were badly depleted of vegetal cover. On July 10, 1936, a storm occurred which was the most intense recorded in Utah in 43 years of record-taking. A recording rain-gage in the watershed gave maximum intensity-readings of 5.04 inches per hour for a five-minute period; 4.32 inches per hour for a ten-minute period; and 3.76

inches per hour for a fifteen-minute period. The duration of the storm was about one hour during which time 1.14 inches of rain was recorded.

During the storm observations revealed no surface-runoff occurred on either the well-vegetated or the terraced areas but surface-runoff did occur on the 15 acres on which the vegetation was deteriorated. Stream-discharge measurements showed that 0.52 inch or a total of 28,234 cubic feet of runoff came from the 15 acres with impaired vegetation and soil-mantle. Using the Horton method of analysis, the average areal infiltration-rate on barren or poorly vegetated areas was about 1.5 inches per hour, while on well-vegetated areas the rate was in excess of 5.04 inches per hour.

These observations and measurements, together with the history of runoff from the drainages as recorded in the deposits at the mouths of the canyons, amply justify the conclusion that many watersheds in the semiarid West may develop a sufficiently complete plant-and-soil mantle to allow an infiltration-rate equal to the greatest magnitude and intensity of storms. The runoff from well-vegetated and deep soil-slopes is often due entirely to channel-interception and ground-water discharge. On the other hand, floods may be induced by the reduction of infiltration-capacity by deterioration of the soil-and-plant mantle and the development of a gully system.

Let us look at the flood-and-erosion history of another canyon in the central Wasatch. Lost Creek, a south-flowing tributary of Provo River, flooded severely in 1938, destroying a power-flume, piling boulders high over the railroad and the State highway, and damming the River. An examination of the cone (Fig. 8) built by runoff from this drainage showed that similar floods had occurred many times in the post-Bonneville period. Similar channels had been cut, debris of comparable size had been deposited, and the River had been dammed at repeated intervals. Active erosion and periodic flooding is a normal characteristic of this watershed.

The slope-conditions agree with the flood-history (Fig. 9). Here 85 per cent of the drainage is made up of steep rocky slopes practically devoid of vegetation. It is evident that the runoff and flood-debris in this 1938 flood, as well as in past floods, came from these steep barren slopes and the drainage-channel. However, within the barren areas are small islands of well-developed soil protected by plant-cover which were neither gullied nor showed other evidence of accelerated runoff. Storms which were sufficiently intense to cause flood-runoff from the naturally barren areas did not disturb well-developed soil protected by a plant-mantle. Here, as in the case of Parrish Creek, runoff characteristics of the drainage were recorded in the surface features of the watershed slopes and in the structure and form of the deposit made at the mouth of the canyon.

These watersheds of the Wasatch Mountains with their contrasting histories and watershed features represent extreme cases where vegetation on the one hand was a primary factor in preventing floods and erosion, and where on the other hand vegetation played no part in the flood-flows. All gradations between these two extremes are to be found.

A geomorphological analysis [6] was made of another western section where pronounced changes in the rate of erosion had taken place. In the Colorado plateau province widespread stream-rejuvenation [7] and accelerated runoff are removing the soil from the watershed slopes and channeling deeply the valley alluvium. These changes have been considered as marking the beginning of a new epicycle of erosion within historic times. Although this recent channeling is insignificant when considered in connection with the carving of the canyons and cliffs of this region, it is of great importance to man, for it challenges his very existence in the Colorado River Basin.

To determine the normality of these changes and the better to evaluate factors influencing erosion, a comparison was made of the gradational processes on drainages that have never been under vegetative control, and on watersheds which have been stabilized for many ages. Bryce Canyon (Fig. 10) in Utah and the Bad Lands near Chinlee, Arizona, provided examples of watersheds without vegetal control and having a high normal rate of erosion; while Kanab Creek, Kitchen Valley, and Johnson Valley (Fig. 11), in southern Utah, are relatively stabilized watersheds. Observations in Bryce Canyon and on the Chinlee Bad Lands reveal evidence of rapid runoff and much deposition, without acceleration. If runoff in recent years had been greatly increased it would have cut channels deeper, made larger deposits, and carried coarser material farther down the fan. The absence of such evidence means that no change of gradient or of climate sufficient to disturb the gradational processes in the region had occurred during the same period of channeling in adjacent drainages.

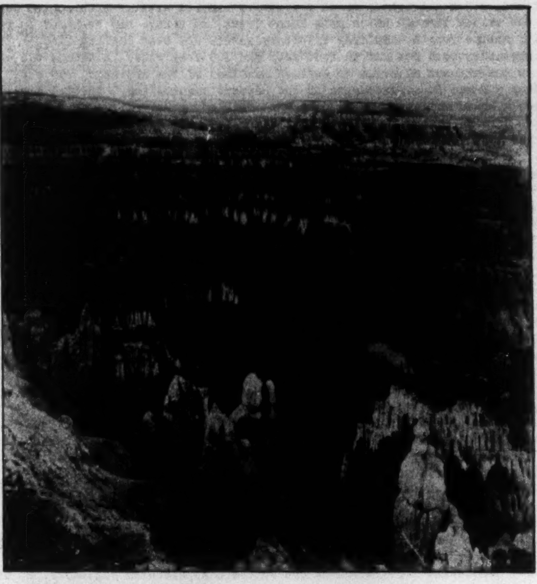


Fig. 10--Bryce Creek drainage, Utah (Here a soil-and-plant mantle has not been developed; erosion is normally rapid and runoff is erratic, often at flood-stage; no change in frequency and degree of erosion and runoff has occurred here during period of greatly accelerated channelling in adjacent drainages)

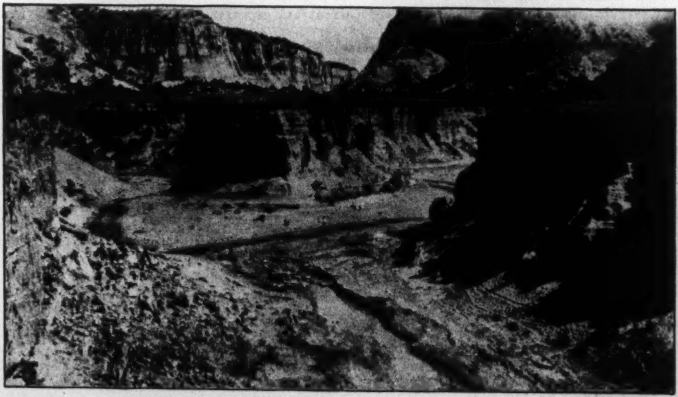


Fig. 11--Post-settlement erosion in Johnson Valley, Utah (Here channelling for the first time since beginning of aggrading cycle is cutting deeply into alluvial fill; modification of soil- and plant-mantle by cutting of roads and trails, overgrazing, and trampling by livestock, and clearing for farming, have changed infiltration-runoff relationship sufficiently to greatly accelerate surface runoff and erosion)

In contrast, other watersheds in this vicinity exhibit greatly accelerated degradation. For example, in the valley through which runs Kanab Creek, an arroyo has been cut in recent years throughout its entire length, and many tributary washes are head cutting through the old alluvium fill. In places this wash has cut 90 feet deep and 300 feet wide. Although old erosion-channels can be seen in the exposed alluvium in certain sections of the drainage, the older erosion did not cut so deep nor was it so extensive as the present channelling. In the upper reaches of this same drainage, a broad valley is being deeply channelled by several washes working back by headward erosion. Here no stream-terraces mark higher stages of valley filling nor is there evidence of buried channels in walls of the exposed alluvium. Absence of such evidence clearly indicates that Upper Kanab Valley has been channelled for the first time since the beginning of the aggrading cycle. This same intensive channelling of the valley fill since settlement occurs generally throughout the region.

In these newly eroding areas the only known general change in the factors influencing the gradational equilibrium of this region was the widespread modification and destruction of the plant-cover.

Summary--Examples have been cited in which a geomorphological approach has been made toward the understanding of erosion- and flood-problems in the semiarid West. The basis for this approach is the general truth that the record of past and present erosion and runoff-phenomena is written in the land-surface--in its forms and materials. Interpretation of this geological-ecological evidence is useful in determining the relation of current gradational processes to normal and in isolating and evaluating the importance of causative factors. From the evidence presented it is concluded that certain watersheds in the semiarid West have normally high rates of degradation; that others have relatively low rates of erosion and runoff due to the development of a plant-and-soil mantle, the binding power and infiltration-rates of which are equal to or in excess of the physical forces of degradation; and that accelerated erosion and runoff have been induced on some areas by a reduction of the normal infiltration-rate and stability of the soil-mantle by deterioration of the plant-cover.

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DISCUSSION OF PAPERS BY C. F. STEWART SHARPE AND REED W. BAILEY

JAY A. BONSTEEL (Soil Conservation Service, Washington, D. C.)--Any attempt to illuminate the "twilight zone" between normal erosion and accelerated erosion is worth while. It is doubtful whether a definite line can be drawn between the two. Normal erosion may become accelerated as a natural process without the interference of man, through a variety of causes, some of which have been suggested in the introduction to Dr. Sharpe's article.

Increased elevation above base-level may be brought about through orogenic movements or through the cutting down of a major stream-channel. Climatic changes may alter the total amount of precipitation, the time in the year of intense precipitation, the form, whether as rain or snow. Ecological changes, resulting in even-aged stands of a single or a few species, accompanied by the shading out of undergrowth, or the reverse, may definitely influence the reception, absorption, and disposition of water. All of these are normal, geologic processes, not influenced by man--in fact, beyond his influence or control.

Normal erosion, or geologic erosion, must remain a purely relative term, capable of adjustment to all conditions from tundra to sand-dune, from arctic to tropical, from humid to arid. It is as varied within its limits as "accelerated" erosion, brought about through the activities of man, is different in the cotton-belt, the corn-belt, the dairy-belt, and in any number of other artificially-established crop-zones.

If it might be said that "normal" erosion is such as occurs naturally in various forms and to different extents under widely different conditions of relief, vegetal cover, climate, and existing soil-conditions, definition would be lacking in the concept, but it would provide for known differences of natural erosion.

If the definition should arbitrarily confine accelerated erosion to the increment of physical soil-removal resultant on man's interference with natural processes, an error would be introduced, as is shown by Dr. Sharpe, since there can not be a definite line drawn between a natural and an artificial increment in removal.

It is an enlargement of the concept of erosion held by some persons to include mass-erosion as one form. This is essential, since erosion should include all forms of mechanical transport of soils and soil-materials, no matter how it may be effected.

In the consideration of stream-erosion under conditions prior to human land-occupation and subsequent to that event, there seem to be certain assumptions on which the Scotch verdict of "not proven" must be passed. Thus, within their channels, streams probably eroded much as they do today. At least, the processes were similar. The quantitative results may have been far different. Outside of their immediate stream-ways, it would be necessary in any specific case to establish identity, similarity, or marked difference. This would be a multifarious job within the continental limits of the United States.

The statement respecting the proportion of permanent and intermittent streams is very probably correct, since every gully with raw banks and a cutting channel is an intermittent stream, and it is capable of proof that their number has been increased many fold within the past 400 years in the United States.

"Slope-wash was prevented." It might be better to say that it was minimized. Slope-wash occurs on all steeper slopes, under any known conditions of vegetal cover, wherever large volumes of water are discharged from nearly level, higher-lying plateau and rounded ridge tops, that have served as accumulators until such a time as their capacity is exceeded. At that point rapid and voluminous runoff occurs, which carries away forest-duff, mineral substratum material, and even cuts pronounced rills and gullies. This is not general, but occasional and local. Yet, it is a recurrent phenomenon in heavily wooded areas and on well-grassed slopes, where natural conditions are at least closely simulated at the present time.

The probable variations in natural cover, in woodland, are well summarized. These are natural and normal conditions from Plymouth Rock to Puget Sound. The "forest primeval" is a beautiful literary concept, but not an accurate scientific basis for evaluating normal and accelerated erosion. Every pioneer who climbed a high tree to look for "windfalls", "burns", "glades", "oak openings", or for a locality where the not-too-dense timber might easily be cleared away and wheat sown or corn planted, could certify to the complex variety of many normal, forest landscapes in the earliest days of the white man's occupation of forested areas. Assuming an even cover of herbaceous vegetation on prairie and plains areas would probably be as grave an error as to assume anything like an even forest-cover over any large area of woodland.

It would be possible to emphasize Dr. Sharpe's statement, "without mantling vegetation there can be no soil-material on slopes steeper than the angle of repose..." to read, "without mantling vegetation, true soils can neither be formed nor retained." This applies all the way from the lichen growing on the rock and contributing organic tissue to the microscopically thin layer of disintegrated matter beneath, up to the climax forest with abundant undergrowth.

Dr. Sharpe, for the sake of emphasis, repeats the term normal in several phrases. What is normal in any one of the instances? A norm is a standard, (a rule). Normal conforms to the established standard. Even if the term natural should be substituted, it would require a vast amount of work to recreate, even mentally, the natural conditions that are assumed to be normal. Man's interference with the natural conditions, as he found them at any given time and at any stated locality, may or may not have increased the activity or widened the extent of soil-erosion. Each specific case would require examination in order to approach to scientific accuracy.

Dr. Sharpe says, "the natural downhill creep of the soil, however, is now of smaller relative consequence than under natural conditions." I must question this. I know of no proof, since I know of no measurements under natrual conditions.

Again, "it is probably smaller in absolute value, etc." I would suggest a tour of some of the older States where stone fences from 150 to 300 years old still exist, making comparisons of soil-profiles above and below the fences, where they run across slopes even of moderate declivity. It would also be well to conduct a study of the downhill creep due to the natural tendency to throw the furrow-slice downhill in plowing operations. This is especially noticeable in localities where "sidehill" plows have been used for some time or where the more modern two-bottom, both-way plows have been used more recently. This down-throw due to plowing will eventually create small bench-terraces where it is used in connection with contour-strip cropping.

Later on Dr. Sharpe refers to "several feet of peaty material, which in most places lies on a thin layer of quartz gravel." Is this true travel--gerollen--indicative of water-action and abrasive rounding while in motion, or is the layer composed of broken, angular, or subangular fragments, gravel in size but not in origin or nature? This is an essential point in the entire argument. If the material is predominantly fragmental, subjected only to slip-movement down a slope then mass-movement of the material is probable but not conclusively proven. It needs supporting evidence. If the material is true, rounded gravel, it very strongly indicates transportation by moving water and may have received its form and acquired its position in several ways, none of them closely related to mass-movement of soils.

In studying Piedmont physiography and the relationship of existing soils and soil-conditions to present altitudes and drainage-ways, to ridges and hollows, it is necessary to recall that the region has been subjected to many changes of land-surface relative to sea-level. It is not merely an old land-surface, long subjected to aerial weathering and denudation. It is an area that has been quite completely below sea-level--at least in Cretaceous times and partly so in later epochs. It has been elevated to its present sea-level relationships through very long periods of time, through discontinuous impulses, some of them undoubtedly involving intervening periods of depression. Even the existing stream-courses are not a normal development on a land-surface of great permanency, but are in some cases courses consequent on the cutting through overlying sedimentary formations, which directed the course of flow as the channels were finally imposed on the underlying consolidated rock-structure.

Stream-channels, filled by oceanic or estuarine sediments, may not have been completely cleaned of such deposits, and there is always the possibility that deposits on an old surface, now forming areas on a ridge or plateau-top, are distinctive fragmentary portions of an old fill, persisting well inside the present accepted boundaries of the Piedmont.

Unquestionably hundreds, probably thousands, of square miles of inner Coastal Plain deposits once overlaid portions of the present Piedmont. These have been partially or completely cut away. Remnants may be expected to survive below an elevation of 1,000 feet anywhere from Alabama to Virginia. Such occurrences must be eliminated in any specific case.

Unquestionably, there have been slow, but decided, changes both in absolute elevation above sea-level and in the [illegible]tive elevations of different parts of the Piedmont with respect to each other. There has been differential elevation, even warping. In attempting to reestablish slope-relationships, such possibilities must be eliminated.

Unquestionably, there have been decided changes in climatic conditions within the area from the warm, humid conditions of part of the Cretaceous to the cooler conditions accompanying glaciation farther to the north. Such changes also have resulted from changed elevation above sea-level, altered distance from the oceanic coast-line, and, possibly, from changes in the nature of the offshore oceanic currents.

There is abundant evidence of soil-creep, well shown by the migration of quartz veins, until they show a bending due to fragmentation, and by the occurrence of areas of markedly different soil-forming materials over characteristic sedentary material. But each case or group of cases needs proof as to its origin.

The fourfold application of principles made by Dr. Sharpe is excellent work.

In the latter part of the paper, there seems to be a dual use of "acceleration." No one would think of combating the idea that there are accelerations of erosion under natural conditions and quite without the intervention of man. He is too late an arrival to be charged with such tremendous accelerations of erosion as provided the materials for the Upper Devonian and Pennsylvanian rocks of the northern Appalachian region. Neither could he be credited with motivating the almost complete cessation of erosion during the Permian, as evidenced by paucity of deposits of that period in the Northeast.

However, man has now intervened to scratch the surface of the Earth for a limited period of time, and evidences of accelerated erosion due to his activities might possibly persist into some future geologic age.

I doubt that "normal" and "accelerated" erosion may be so concisely defined as to include, in each case, all conditions that it is intended to specify and to exclude all other conditions. There is such an interlocking and overlapping of natural and artificial processes and so little real definite knowledge of conditions antedating the use of soils by man that definition is impractical. It is only by inference that man may establish conditions antedating his appearance on the scene.

Even reports of early white explorers merely represent what they saw after the landscape had been influenced to some extent through the occupation of portions of the continent by men who had advanced to a condition of settled domicile, agricultural support of a hunting and fishing existence, and even to irrigation, to the development of the main types of maise to at least four subtypes, and to the utilization of both forest- and field-products to such an extent that the earliest colonists were dependent upon their stored supplies and their knowledge of plants and tillage for their preservation from starvation.

Dr. Sharpe's paper, reporting on specific cases of soil-movements, opens a field of research of great importance. It would seem to be desirable that similar studies should be made in other localities in the Piedmont and in other physiographic provinces in order to build up a mass of definite observations on which general hypotheses may be based and from which general rules may be derived.

E. G. ZIES (Geophysical Laboratory, Washington, D. C.)--Accelerated erosion in volcanic areas: In this brief discussion attention is directed to a type of accelerated erosion caused by dry rock moving swiftly over a steep gradient. It is probable that this effect is characteristic of regions in which the material ejected by the volcano is laid down in alternating layers of fine ash and heavy fragmental rock.

In 1902 an explosion at the 7,000-foot level on the flank of the volcanic cone of Santa Maria, in Guatemala, developed a crater and dislodged the surface-material above to a height of 12,000 feet. This 5,000-foot scar permits one to see that the cone is built up of alternating layers of fine ash, fragmental rock, and flows of lava.

Rainfall at this elevation is only moderate and its effects are not pronounced. Wind-erosion of the ash is pronounced and causes the overlying fragmental rock and lava-blocks to move down the steep slope (gradient about 50°) with enormous velocity. The scouring action is developing deep V-shaped grooves in the exposed flank and is obviously cutting down the upper portion of the volcanic cone.

It has been repeatedly observed that the rock-falls are infrequent or absent during a fall of rain and during periods of low wind-velocity. They are resumed with great intensity as soon as the sun had dried the layers of ash, this permitting rapid erosion by the prevailing winds.

C. R. HURSH (Appalachian Forest Experiment Station, Asheville, North Carolina)--Geomorphic aspects of normal and accelerated erosion: In his discussion of the Eastern States, Dr. Sharpe has brought out the importance of mass-movements of soil down slope by creep, under certain conditions of high infiltration and deep soils. He has indicated also that under these same conditions occasional events may give rise to forms of accelerated erosion. A particularly good example of these latter phenomena is found in the mud-flows that occur in the high rainfall-area of the Appalachian Mountains.

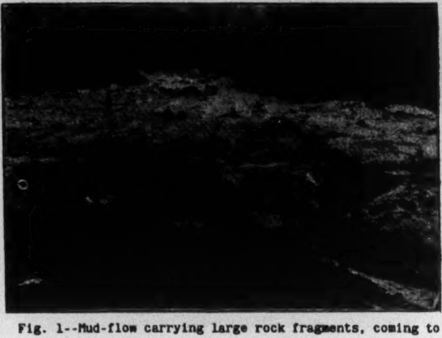


Fig. 1--Mud-flow carrying large rock fragments, coming to rest on a mountain valley cornfield, Macon County, North Carolina, August 30, 1940 (Photo by U.S. Forest Service)

Small slides and slips resulting in mass soil-movement are of quite common occurrence and have frequently been discussed in the literature. Large slides are also reported in deep soil-areas, that form temporary dams in mountain streams and induce additional bank-cutting when they are broken. Mud-flows are much less well known in the Southern Mountains. This is partly because of the rank growth of vegetation that soon masks their spectacular appearance. Also in any one locality large mud-flows may occur only infrequently. Many local inhabitants even in sections where mud-flows occur have never actually witnessed one of them. Consequently there are many conflicting stories as to their occurrences and appearance.

What actually happens is the saturation of a deep colluvial soil-accumulation lying at the lower portion of a steep mountain slope. After a period of prolonged rainfall the colluvial soil-mass becomes so charged with water that any major break of the surface may start a mass-movement. For example, the blowing over of a large tree and sudden removal of a mass of soil with its roots may produce sufficient disturbance of the soil to start the mud-flow. The nature of the movement of the soil-mass depends on the slope of its contact-zone with stable material.

The amounts of soil moved may cover as much as several acres of land after it comes to rest on level terrain. Large rocks weighing 50 to 200 tons may be floated into the level valleys. These large rocks known to have been transplanted into a valley during recent mud-flows are similar in every way to other rocks that were in the valley before settlement. It is obvious that mud-flows in the Southern Appalachians have had and are still having a very considerable influence on the geomorphy of the mountain valleys.

Dr. Sharpe's emphasis on detailed studies of the processes and land-forms of natural accelerated erosion is quite as applicable for the Archean formations in the Southern Appalachians as for the Piedmont. Both loss of life and property can be avoided by a better knowledge of the location of areas of potential mud-flows and major landslides.

GEORGE B. CRESSEY (Syracuse University, Syracuse, New York)--I think it is particularly appropriate that this discussion be under the leadership of Dr. Lowdermilk because I remember discussing normal and accelerated erosion with him some two decades ago while in the field in China. It is quite obvious that man has accelerated erosion in some places. However, these illustrations from the Southwest and the Piedmont are not typical of all the United States. In New York State large areas of forest have been replaced by pasture and grass-lands, rather than by cultivated crops. The surface thus remains blanketed by vegetation as before. The perfection of glacial features over much of the State indicates the negligible extent of accelerated erosion. It is locally important but still a minor phenomenon.

PETER E. WOLFE (Princeton University, Princeton, New Jersey)--Subsequent topography, an expression of structure, lithology, and soil: Structure, lithology, and soil are important factors in controlling the development of the erosional land-forms in the Frenchtown, New Jersey, and East Greenville, Pennsylvania, areas of the Piedmont Triassic lowlands. It has been found that in a humid climate fluvial erosion acting on a series of plunging synclines, anticlines, and monoclinal dipping rocks, has etched out a topography, the details of which correspond intimately with the structure, lithologic, and soil variations. It is demonstrated that differential erosion of lithologic units in a humid climate is in reality accomplished by the erosion of soils which mantle the respective units rather than the bed-rock itself. It is only under limited circumstances such as stream-bed channels and some gully beds that bed-rock itself is eroded.

The erosional pattern differences on the scarp- and dip-slopes of the strike valleys developed on the monoclinal dipping rocks are attributed to soil-erodibility differences which in turn are due to lithologic and structural differences. The dip-slope is eroded to a fine-textured corrugated pattern with many closely spaced shallow gullies whereas the scarp-slope is eroded to a coarse-textured pattern with few widely spaced dales. These erosional pattern differences are due to lithologic and corresponding soil-erodibility differences. The soil which overlies the grey-blue argillitic shale on the dip-slope has a dense clayey hardpan-like "B"-horizon which is very resistant to erosion. Once a gully cuts through the "A"-horizon, further down-cutting is greatly retarded by the hardpan layer and therefore shallow gullies result. In contrast, the soil which overlies the red shale on the scarp-slope lacks a hardpan "B"-horizon and therefore gullies cut through the "A"- and "B"-horizons to the weathered bed-rock, and consequently the gullies are deep.

The broad synclinal uplands and narrow anticlinal valleys have been formed by peneplanation of plunging parallel folds and by the subsequent uplift with sculpturing during the present erosion-cycle. Structural lines of weakness, such as the concentration of fractures in the crests of anticlines, has been important in the development of anticlinal valleys. Tributaries to the anticlinal valleys develop along the strike of soft shale-beds, along faults, and along badly fractured areas where tight folding and bending has shattered the shale-beds. The soils mantling the hard and soft red-shales of the plunging folds of the synclinal uplands have themselves been differentially eroded to a strike vale and ridge topography, the details of which correspond intimately with the lithologic and soil-variations.

ROBERT T. KNAPP (California Institute of Technology, Pasadena, California)--A concept of the mechanics of the erosion-cycle: The following remarks are made less as a discussion of the first paper in this symposium than as a preface to the ones that are to come.

The title of the symposium is a very thought-provoking one--"Dynamics of erosion in a new land." It would have been very normal to have left off the first two words and simply to have called it "Erosion in a new land." So why the "dynamics"? One straightforward way of attempting to answer that question is to turn to the dictionary. This yields: "Dynamics--branch of mechanics treating of motion of bodies and the action of forces in producing or changing this motion." This definition demonstrates at once how appropriate the title really is, because fundamentally erosion is a mechanical process whose vital components are the forces which cause erosion, those which resist it, and the resulting motion of the eroded material. To master the problems of erosion and be in a position to work with them intelligently, the whole process must be studied and understood. The unfortunate fact is, however, that most of us are so engrossed in attempting to check or forestall erosion that we are apt to concentrate all our efforts on devising preventive methods without taking the time to study and evaluate either the forces or the mechanism of erosion. Therefore, this symposium, in emphasizing that resistance to erosion is only one phase of this complex problem, is doing us all a distinct service by furnishing us new viewpoints from which to approach our task.

The erosion-process can be thought of as a cycle which is made up of three parts, namely, entrainment, transportation, and deposition. One remarkable thing about this cycle is that it exists in all its details in a tremendous range of sizes. All of us are familiar with the typical river-system which entrains material in the head-waters, transports it long distances, and finally deposits that material on the delta. That is the erosion-cycle on a grand scale.

Figure 1 shows another such erosion-cycle, somewhat smaller, it is true, but still with all of the three component parts working together. The zone of entrainment is seen in the head-waters, the material has been transported from there down to the mouth, and then deposited to form a delta. A glance at the next illustration is necessary to determine that this all happens in only a few inches. It is rather significant that these two examples of the erosion-cycle, one five million times larger than the other, both have the same general characteristics.

If the three divisions of the cycle are examined in more detail, it is seen that they are simply three different phases of the struggle between the forces tending to cause motion of the soil-particles and the forces resisting that motion.

In the zone of entrainment if the resisting forces are equal to or greater than those trying to cause entrainment, there is, of course, no erosion. On the other hand, active erosion indicates that the balance is the other way. In the zone of pure transportation, that is, where no new material is being picked up from the bed, the forces may be thought of as being in equilibrium; and in the zone of deposition it is clear that the forces trying to prevent motion have secured the upper hand. From this point of view it is seen that the whole erosion-cycle

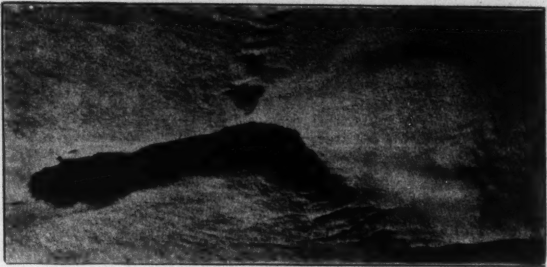


Fig. 1--Typical erosion-cycle in arid country

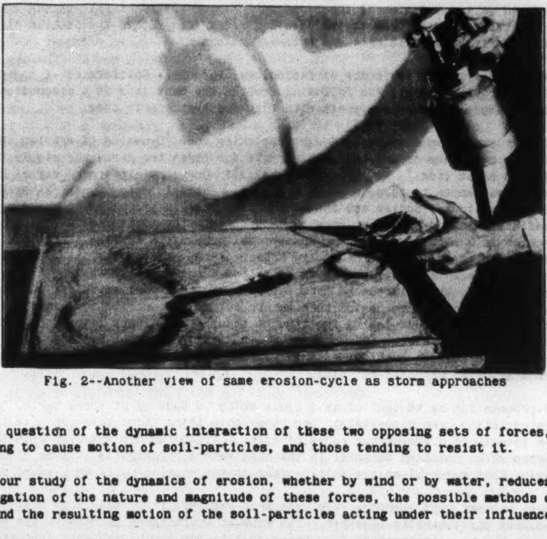


Fig. 2--Another view of same erosion-cycle as storm approaches

is simply a question of the dynamic interaction of these two opposing sets of forces, that is, those tending to cause motion of soil-particles, and those tending to resist it.

Thus, our study of the dynamics of erosion, whether by wind or by water, reduces itself to the investigation of the nature and magnitude of these forces, the possible methods of modifying them, and the resulting motion of the soil-particles acting under their influence.

Investigators of methods of preventing soil-erosion have the choice, therefore, of only two approaches. These can be used either singly or in combination. They are, obviously, either the strengthening of the forces resisting soil-motion or the weakening of those of entrainment.

Figure 3 is a preliminary classification and subdivision of the forces acting in all three divisions of the erosion-cycle. This is proposed with the hope of furnishing a systematic basis for their further investigation. All of the papers presented in the symposium deal with various sets of these subdivisions. Taken as a whole, they can be fitted together to give an overall picture of the problem of erosion.

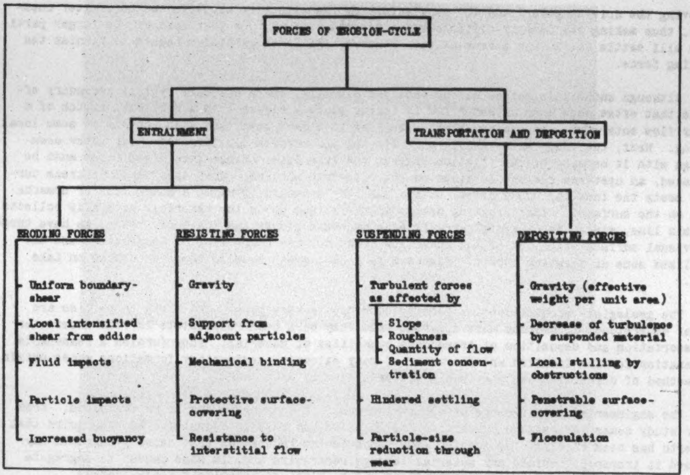

FORCES OF EROSION-CYCLE
ENTRAINMENT
TRANSPORTATION AND DEPOSITION
ERODING FORCES
RESISTING FORCES
SUSPENDING FORCES
DEPOSITING FORCES
Uniform boundary-shear
Local intensified shear from eddies
Fluid impacts
Particle impacts
Increased buoyancy
Gravity
Support from adjacent particles
Mechanical binding
Protective surface-covering
Resistance to interstitial flow
Turbulent forces as affected by
Slope
Roughness
Quantity of flow
Sediment concentration
Hindered settling
Particle-size reduction through wear
Gravity (effective weight per unit area)
Decrease of turbulence by suspended material
Local stilling by obstructions
Penetrable surface-covering
Flocculation

Fig. 3--Classification of forces acting in the erosion-cycle

ROBERT T. KNAPP and HUGH STEVENS BELL (California Institute of Technology, Pasadena, California)--Density-currents: Density-currents form one subdivision of the problem of transportation and deposition of eroded sediments. Since they have been recognized only recently as a significant component in the erosion-problem, a working definition of them is desirable. A density-current may be described loosely as a gravity-flow of a fluid through, under, or over a fluid of approximately equal density. For the present purpose, this definition is too inclusive, since it covers many types of density-currents not pertinent to our problem.

The cause of the current is always a density-difference, which for the cases significant to the erosion-problem, is produced by soil-particles suspended in the fluid. Although such density-currents can occur both in water and in air, only water-currents will be discussed here. Thus, although dust storms usually are true density-currents, they will not be considered.

Density-currents furnish one important way in which sediments are transported by water. However, there is a very striking difference between a sediment-laden flow in a river and the same flow after it has entered a reservoir and become a density-current. In the open channel the water transports the sediment, but when the same flow enters a reservoir, the sediment transports the water. This complete reversal of the roles of the two flow-components is responsible for many of the characteristics of density-currents. Although it was formerly believed that density-currents occurred only rarely, were very delicate, and were destroyed or dissipated with extreme ease, it is now being demonstrated that their existence is the rule rather than the exception, that they are difficult to prevent and more difficult to destroy. The reason for this misconception is that the most important cases are underflows in lakes, reservoirs, and oceans, and, therefore, are not visible. When a muddy stream enters a clear reservoir, either the stream mixes uniformly with the reservoir-water or it becomes a density-current. At the entrance, the collision of the stream with the reservoir-water liberates a large amount of energy, which, although it produces dilution, rarely causes mixing sufficiently thorough to present the formation of a density-current.

After the underflow has started, mixing can take place only across the interface between the muddy water and the overlying clear water. This mixing is a relatively slow process and can rarely be expected to destroy the flow, since to do so it must first destroy the density-difference, and the time of transit is normally too short to do this. There seem to be only two methods of stopping such a density-current: (a) By settling out the suspended sediment, thus removing the driving power; and (b) by eliminating the effective slope in the underwater channels, thus making the density-difference ineffective. It is true that most of the larger particles will settle out in the stream-delta. However, the finer particles remain to furnish the driving force.

Although underflows seldom can be observed directly, there are some typical secondary effects that often show when an underflow is taking place. Figure 1 is a sectional sketch of a muddy flow entering a reservoir. First, the flow is slowed down, and this results in some local mixing. Next, the muddy water starts underflowing and carries considerable clear water downstream with it because of the friction-drag at the interface. Since this clear water must be replaced, an upstream current develops on the reservoir-surface. When this clear upstream current meets the incoming muddy river, both flows turn downward, forming a sharp line of demarcation on the surface. Also, floating debris in the stream or on the reservoir naturally collects on this line, since the currents carry it here and then plunge and leave it. Thus, we have these two visual surface-evidences of the underflow, that is, the sharp line of demarcation and the localized zone of floating debris. Figure 2 is a photograph showing these evidences on Lake Mead.

The geological significance of density-currents is very great. As their properties are better understood, it becomes more apparent that they have been responsible for the underwater transportation and deposition of tremendous quantities of material. They furnish a reasonable explanation for the location and character of many extensive sedimentary formations whose origin and method of deposition had previously not been clearly understood.

The engineering significance of density-currents is only beginning to be evaluated. From their study comes information concerning the location and rate of deposition in reservoirs that hitherto has been lacking. Of greater importance is the indication that density-currents may be used to transport sedimentary material through reservoirs and, in some cases, to segregate and withdraw from the reservoir certain flows which, although relatively clear, carry

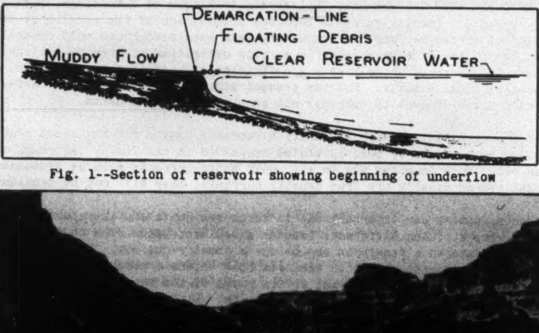


Fig. 1--Section of reservoir showing beginning of underflow

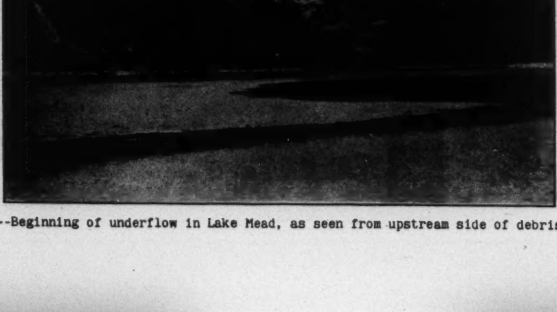


Fig. 2--Beginning of underflow in Lake Mead, as seen from upstream side of debris-zone

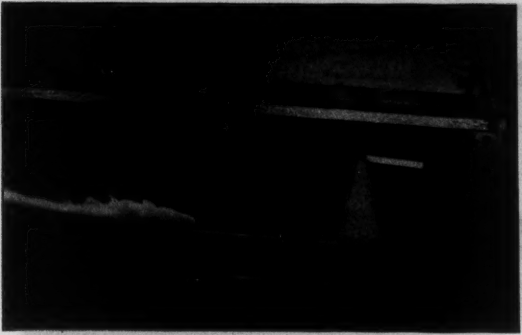


Fig. 3--Muddy underflow entering clear reservoir

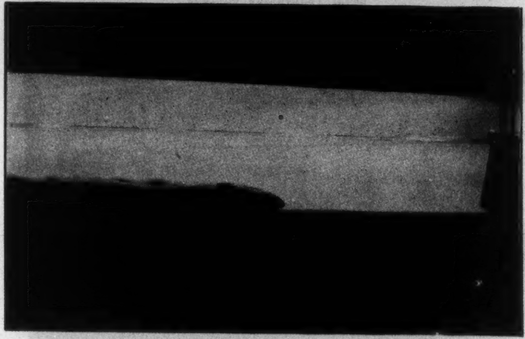


Fig. 4--Subsequent lighter underflow enters reservoir and flows on top of first layer

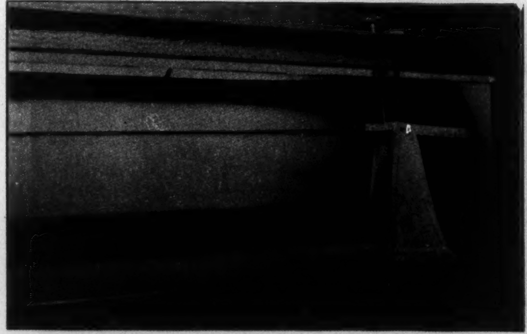


Fig. 5--Layering in reservoir after flows have ceased

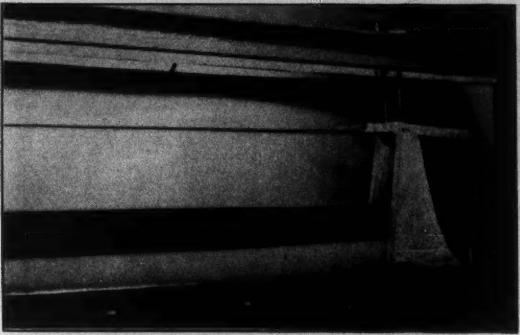


Fig. 6--Controlled withdrawal at both layers through their respective outlets

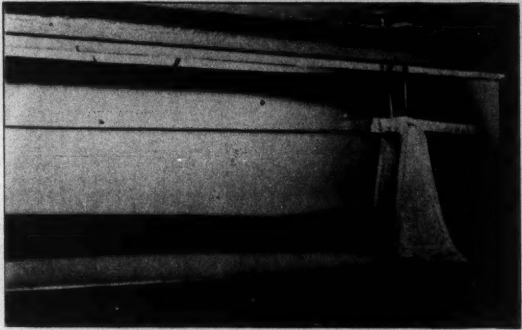


Fig. 7--Excessive rate of withdrawal from lower outlet results in mixed flow from both layers

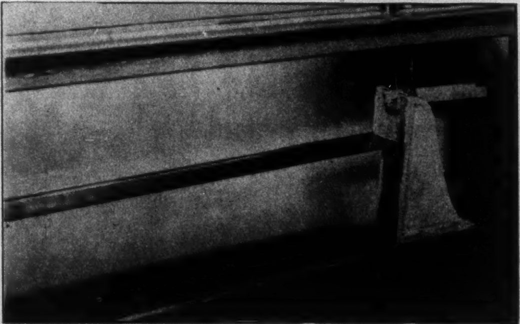


Fig. 8--Mixture of clear and muddy water being discharged through lower outlet due to excessive withdrawal rate

RECENT DEVELOPMENTS IN THE DYNAMICS OF WIND-EROSION

Frank J. Malina

Introduction

Those particles of the Earth's land-surface that are in contact with the atmosphere are at the mercy of two powerful natural forces, resulting from water- and air-flow. The story a single soil-grain could tell of its travels would surpass that of Marco Polo. It is unfortunate that one cannot "get the story" and thus answer many questions that are in the minds of those who wish to explain and control its behavior.

The transport of granular material by fluids has been a subject of intense interest, especially in connection with flowing water. A great number of investigations have been made, both in the laboratory and in streams, on the effects of water-erosion and the underlying mechanisms of the movement of debris. As a result, at least for some phases of the process, explanations and empirical rules have been developed.

When one turns to the problem of the transport of soil by wind, a much less satisfactory situation is found. Within the last decade, a pressing need has arisen in the United States for an understanding of the fundamental principles of wind-erosion due to the severe movement of soil in the Great Plains region. The phenomenon of the "dust-storm" has become familiar, even in the City of Wasnington--2,000 miles distant from the region in which the particles were carried aloft.

To the soil conservationist fell the responsibility for developing methods of checking this destruction of vast areas of valuable land. The necessity of doing something quickly to alleviate a suddenly critical situation brought about an almost "panicky" search for a solution.

The most obvious way of evaluating proposed control-methods lay in trying them in the field. A large number of such investigations have been conducted to determine the defectiveness of various land-use methods and the effectiveness of corrective measures. Experiments of this type are of primary importance; however, they are handicapped by dependence on the whim of the weather, the often objectionable length of time needed to obtain data, and in many instances the prohibitively large cost. The fact that a control-method recommended in one region may not succeed in another further restricts the value of the field-studies.

To these difficulties must be added the inherent complexity of the problem. In Table 1 some of the variables that play a greater or lesser part and some of the surface-effects that result are listed.

Table 1

Wind	Surface	Topography	Soil	Surface-effects
Speed	Roughness	Flat	Texture	Removal
Direction	Cover	Undulating	Structure	Deposition
Structure	Obstructions	Broken	Organic content	Surface-markings
Temperature	Temperatures		Moisture-content	Dune-formation
Humidity			Soil-binders	
Burden carried				

The number of situations that can be set up by making combinations of the variables listed in Table 1 is seen to be very large. The following problems are of basic importance and are, therefore, the ones upon which research has been concentrated:

(a) The mechanism of lifting the soil from surfaces and the mechanism of transportation and deposition of particles
(b) The dependence of the amount of soil blown on the velocity and turbulent structure of wind
(c) The effect of the soil-surface and suspended soil on the velocity-distribution and structure of wind
(d) The distribution of transported soil-particles above the surface
(e) The effectiveness of obstacles of different kinds in preventing soil-blowing
(f) The mechanism underlying the formation of dunes and drifts, and methods of reclaiming such areas

The problems of the soil conservationist in fighting wind-erosion are similar to those encountered by the pioneers in the development of aircraft. The modern airplane has been made possible to a large extent by experimentation using a suitably directed, artificially produced wind. The device used in this research is known as a wind-tunnel.

In the following sections, the wind-erosion process will be hastily reviewed and the recent introduction of the soil-blowing tunnel, as an aid in predicting the behavior of exposed soil-surfaces to wind, will be discussed.

(1) The wind-erosion process--General remarks

The wind--In the practical problem of combating wind-erosion, the interaction between the prime mover--air--and exposed soil-surfaces of diverse character, must be understood before effective control-methods can be developed.

An air-stream, moving over a surface, can be described by the variation of its mean velocity and its turbulent structure with height above the surface. The layer of air, extending roughly to a height of the tallest obstruction in the field, is of major importance for nothing can be done purposely to influence the transport of particles once they exceed this height.

When turbulent unladen air flows over an unobstructed flat surface, the variation of the mean velocity of motion, u, parallel to the surface, with the height, z, is well represented by Prandtl's extension to the atmosphere of von Kármán's logarithmic relation

$$u = 5.75\sqrt{\tau/\rho}\ \log_{10}(z/k) \qquad (1)$$

where τ is the friction per unit area acting on the surface, ρ is the air density, and k is a roughness factor, usually taken as 1/33 to 1/30 of the average diameter of the surface-elements.

In Figure 1 velocity-profiles obtained for air flowing in an open channel and a rectangular working section of a wind-tunnel are compared with the profile of a natural wind, calculated from (1), with k corresponding to a fixed sand-surface of 0.01-inch diameter grains.

The effect of various types of ground-surfaces on the velocity-distribution, as measured by Chepil and Milne with a portable field-tunnel, are shown in Figure 2.

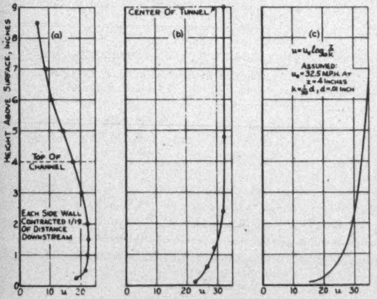


Fig. 1--Velocity-profiles obtained in (a) open-top channel with contracted side walls, (b) rectangular working section of California Institute of Technology soil-blowing tunnel, and (c) calculated from logarithmic relation

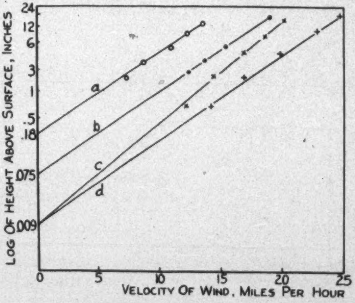


Fig. 2--Wind-velocity gradients, obtained over various types of ground-surfaces in a portable soil-blowing tunnel: (a) Level ground-surface covered with a growth of bromegrass about six inches high; (b) rather thin, irregular wheat stubble, about seven inches high; (c) smooth, level, bare ground; (d) same as (c) with wind-velocity increased (Measurements of W. S. Chepil and R. A. Milne)

Turbulence in the wind--In expression (1), for the variation of velocity with height, it is important to notice that it is an expression for the *mean* velocity of motion. The actual wind is turbulent, that is, upon the mean velocity, measured with an averaging instrument, such as a pitot-static tube, there are superimposed velocity-fluctuations, due to the existence of eddies in the flow. G. I. Taylor has defined turbulence as follows: "Turbulence is an irregular motion which in general makes its appearance in fluids, gaseous or liquid, when they flow past solid surfaces or even when neighboring streams of the same fluid flow past or over one another."

Further, to paraphrase von Kármán: "Common language, even in technical papers, uses the term *turbulence* in a rather indefinite way, including in it for instance, *vortex motion* in general. The scientific term *turbulence* implies *irregular fluctuations*, governed by laws of some statistical equilibrium. To be sure, turbulence may be originated by vortices resulting from the flow through a honeycomb; but we call such a motion *turbulent* only if the regular pattern, because of the intermingling of a great number of vortices, disappears, as happens further downstream from the honeycomb. Similarly, vortices produced by obstacles at the ground contribute essentially to atmospheric turbulence, but also in this case we restrict the term turbulence to the statistical phenomenon of the mass-exchange and keep this case apart from other conceptions, such as individual vortices (tornadoes, vortex sheets, etc.) or regular atmospheric waves."

Turbulence is the subject of intense investigation in fluid mechanics at the present time. The results, thus far obtained, indicate that for a turbulent flow, in which the velocity-fluctuations in the three orthogonal directions (x,y,z) are denoted by (u',v',w') can be described: (a) By the *turbulence-level* (or intensity), whose value is given by the ratios of the root mean square of the velocity-fluctuations $\sqrt{\overline{u'^2}}$, $\sqrt{\overline{v'^2}}$, $\sqrt{\overline{w'^2}}$ to the mean velocity u; and (b) by the *scale of the correlation-function* measured, for example, by the distance between two points, for which the correlation-function of a certain velocity-component has a given value.

Assume that the velocity-fluctuation u' has the values u'_1 and u'_2 at two points P_1 and P_2, then the ratio $\overline{u'_1 \, u'_2} \Big/ \sqrt{\overline{u'^2_1}} \sqrt{\overline{u'^2_2}}$ determines the correlation-function for u'. The distance at which the function drops to a certain value, say one-half, is a measure of the scale of the correlation.

The turbulence-level gives a measure of the intensity of the velocity-fluctuations, and the scale of the correlation-function a measure of the physical size of the eddies. Figure 3 is an example of the intensity of the velocity-fluctuations in a wind-tunnel, and Figure 4, an analysis of wind-structure near the ground.

One more modern fundamental concept developed in connection with turbulent flow needs mentioning. That is the concept of the turbulence exchange-coefficient or kinematic eddy-viscosity ϵ. In the case of laminar flow, the interaction between adjacent layers is made evident by molecular friction and the shearing stress τ is given by the product of the kinematic viscosity μ and the gradient of the velocity (du/dz), that is, $\tau = \mu$ (du/dz).

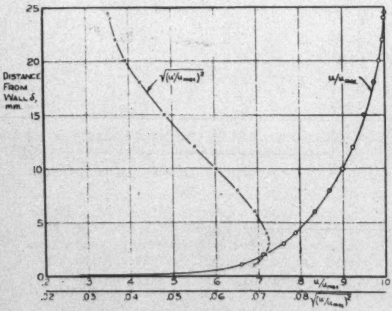


Fig. 3--Distribution of mean velocity and velocity-fluctuations in wind-tunnel of rectangular cross-section with large aspect ratio (Measurements of Wattendorf and Knoblock, California Institute of Technology)

When the flow becomes turbulent, in addition to molecular interchange, lumps of fluid are transported from one layer to another, and the shearing stress is given by the momentum transferred through unit-area in unit-time, or $\tau = \epsilon \dfrac{d}{dz} (\rho u)$.

The exchange-coefficient ϵ in addition to acting as a viscosity-coefficient, also gives an indication of the range of penetration of the turbulent eddies that serve as carriers of transferable quantities such as heat, momentum, and soil-particles.

Obstructions--Consider, for example, an unladen wind that starts over a sandy plain with a velocity-distribution given by (1) and possessing a definite turbulent

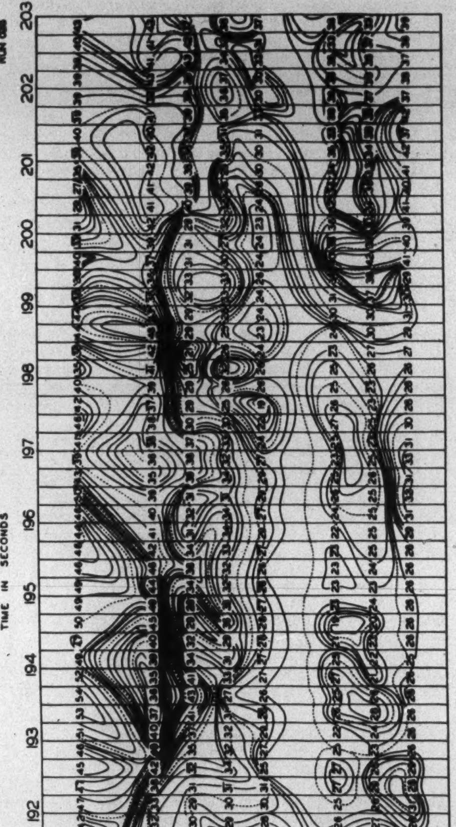


Fig. 4--Analysis of wind-structure near ground showing lines of equal velocity as function of height and time (Measurements of R. H. Sherlock and M. B. Stout) structure. As it moves across a typical countryside, it encounters surfaces of varying roughness and obstructions of different kinds that alter and distort its velocity-distribution and vary its turbulent structure. For simplification, obstructions will be understood to denote localized obstacles that influence the wind as opposed to cumulative effects of large areas, covered more or less uniformly with similar obstacles. The latter can be thought of as surfaces of macroscopic roughness. Under this classification the following are obstructions: Windbreaks, fences, terraces, embankments, buildings, and crop-strips.

It is convenient at this point to discuss briefly an important law of fluid flow discovered by O. Reynolds. It states that, for flows around two geometrically similar bodies to be dynamically similar, the ratio, known as Reynolds Number

$$(\rho U \ell / \mu) = Re \qquad (2)$$

must have the same value. In the above relation, ρ is the density of the fluid, U is the velocity of flow, ℓ is a characteristic length of the body, and μ is the viscosity of the fluid.

Although the Reynolds Number was originally developed for the consideration of flow of fluids around solid bodies, its importance has extended into all phases of fluid mechanics. The Reynolds Number and turbulence have been called by H. L. Dryden the companions that determine the character of fluid flow.

The natural wind, in flowing over obstructions of different types on the ground, can, therefore, be expected to be influenced by their size and shape. Windbreaks and certain other obstacles add another factor to affect the flow-pattern, in that they possess porosity.

Soil--The soil adds many factors to the problem, due to its varied physical nature. It is made up of solid, liquid, and gaseous components. The effect of the last two components on the erodability of soil by wind is largely unknown.

The solid portion of soil is made up of inorganic and organic matter. The inorganic part is composed of mineral particles, which are classified, according to size, into three principal groups, called sand, silt, and clay. The particle-sizes have been arbitrarily fixed at diameters of 2 to 0.05 mm for sand, 0.05 to 0.002 mm for silt, and less than 0.002 mm for clay.

The texture of soil is determined by the proportion of the particles of different size that a sample contains. Figure 5 shows the distribution of particle-size in a sample taken from a barchan dune near the Salton Sea in California, and Figure 6, the per cent of sand, silt, and clay in soils of various texture.

Individual grains of soil determine its texture and their arrangement its structure. Some of the types of structure are single grain, crumb, granular, fragmentary, mulch, prismatic. shot, angular, nut, etc.

The susceptibility of unprotected soil to blowing is dependent to a large extent on its texture and structure. Since these two physical characteristics change in a soil-profile, it is possible that an area have varying rates of erosion as the surface is lowered.

An important aerodynamic quantity of an individual grain is its terminal velocity of fall through air. Grains differ from one another, not only in size and composition, but also in shape, which affects their settling velocity. The shapes of Nevada white-sand particles, taken from a sample having a geometric mean sieve diameter of 0.47 mm, are shown in Figure 7. It is usual practice to consider a sample as made up of spherical grains, whose rate of fall is equivalent to the average rate of fall of the actual grains. The settling velocity of quartz spheres in air and water is plotted in Figure 8.

(2) The initiation of the movement of soil

The wind-erosion process consists, in general, of three distinct phases--initiation of the movement of soil-particles, their transport, and their deposition. The mechanisms underlying the phases are not as yet clearly understood; however, on the basis of investigations thus far made and analogies drawn from the transport of debris by liquids, a number of hypotheses have been advanced.

When this section was being planned, it was intended to summarize the various theories advanced in connection with liquids for the initiation of soil-movement. However, upon reading

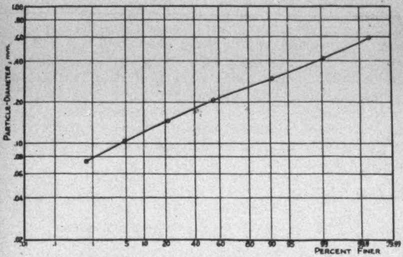


Fig. 5--Sand-particle-size distribution in sample taken from barchan dune, near the Salton Sea in California

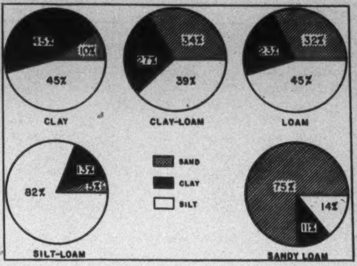


Fig. 6--Per cent of sand, silt, and clay in soils of various textures (According to Rice and Alexander)

the most recent discussion of the problem by H. A. Einstein, it was felt that only a picture of the forces acting in the process was in order. Einstein makes the statement:

"Attempts have been made in the past to derive an expression for the initial movement that is governed by certain definite critical conditions to be used as the first step toward the solution of the transport-problem. In interpreting the results of many experiments on bed-load movement, and in comparing them with those obtained by other experimenters the writer has concluded that a distinct condition for the beginning of transport does not seem to exist. It is just as impossible to determine the limit of initial movement as to determine the maximum possible flood of a river."

This statement requires further verification, for the critical factors controlling the initiation of movement of soil-particles are of great importance in the prevention of erosion by wind.

Fig.7--Photomicrograph of Nevada white sand of 0.47-mm geometric mean sieve diameter, magnified 5 diameters

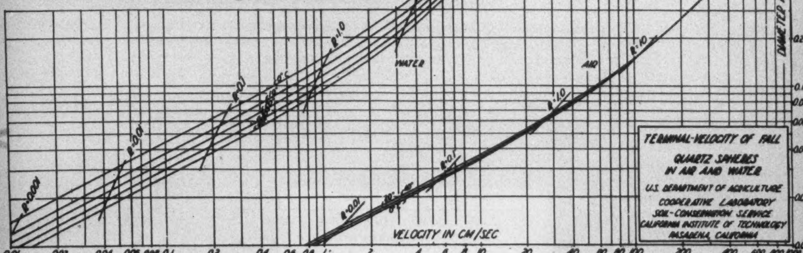


Fig. 8--Settling velocity of quartz spheres in air and water (Prepared by H. Rouse)

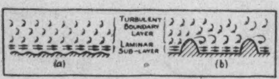


Fig. 9--Schematic diagram showing laminar sub-layer and roughness (a) not affecting and (b) affecting the main turbulent flow

A closer study of the nature of fluid flow near a surface shows that the relation (1) for the distribution of mean velocity holds satisfactorily in a fully developed turbulent flow. When a fluid moves over a surface the boundary-layer has been found to consist of two regions of flow. Very close to the surface the motion is laminar and the region is known as the laminar sub-layer (Fig. 9). The main turbulent region above is not affected by the surface-roughness until the roughness-elements emerge through the laminar sub-layer. S. Goldstein found that roughness elements of height d would be within the laminar sub-layer as long as

$$d\sqrt{\tau/\rho}/\nu \leq Re_c \leq 4 \tag{3}$$

where ν is the kinematic viscosity of the fluid and Re_c is the critical Reynolds Number.

Particles making up the surface are, therefore, acted upon by forces according to the type of flow about them. Thus in the laminar sub-layer viscous stresses predominate, in the transition-region from laminar to turbulent flow, viscous and Reynolds stresses are of the same order

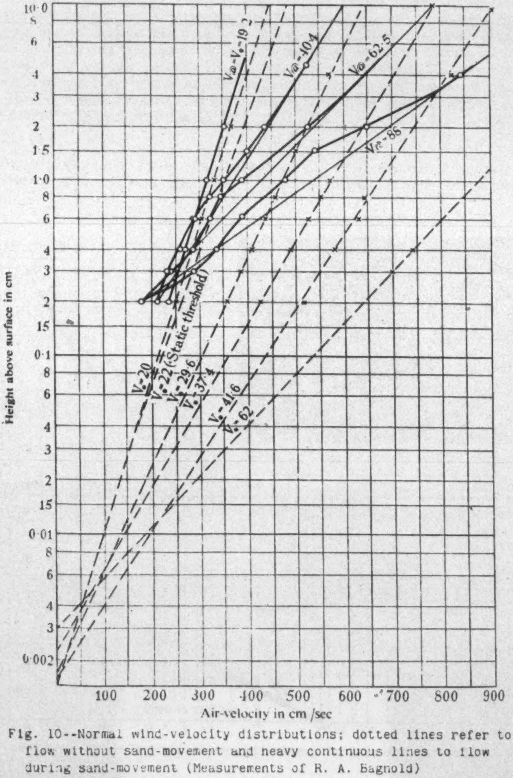


Fig. 10--Normal wind-velocity distributions; dotted lines refer to flow without sand-movement and heavy continuous lines to flow during sand-movement (Measurements of R. A. Bagnold) of magnitude, and in the fully turbulent region only Reynolds stresses need be considered.

P. Nemenyi classifies the mechanical forces acting on an individual grain as follows:

(a) Forces exerted upon the grain-surfaces by the fluid (F_f)
(b) Terrestrial gravity--weight of grain (F_w)
(c) Surface-forces both normal and tangential exerted by other grains (pressure-, friction-, and impact-forces) except those caused by mass-attraction (gravitation) between grains (F_s)
(d) Forces exerted by other grains in consequence of mass-attraction--cohesional influences (F_c)
(e) Inertia forces (F_i)

Since, in connection with wind-erosion, little is known of the effect of the above forces, it is necessary to know under what conditions the conclusions obtained with liquids can be applied. Nemenyi states that the simplest assumption for the existence of dynamic similarity is that the ratios F_f/F_i, F_w/F_i, F_s/F_i, and F_c/F_i should be the same for corresponding grains.

A number of semi-empirical formulas have been developed for the determination of the critical conditions under which particles begin to move. The starting point in the derivation of the formulas is the equilibrium of an individual particle. If a particle were spherical in shape and isolated, the problem would be quite simple; however, the fact that shape and size vary and that each particle in a bed is influenced by its neighbors, has made it necessary, thus far, to introduce empirical coefficients. These vary to such a large extent to meet different conditions of flow and surface that no rational description of the process in general can be drawn.

R. A. Bagnold has carried out a comprehensive investigation on the transport of desert sand by wind. In connection with the initiation of particle-movement, he defines a "static threshold wind," the value of which he found to depend on (a) the former history of the surface, (b) the extent to which sand-removal has collected a protective layer of the biggest grains on the surface, (c) on the surface-turbulence of the wind, and (d) on the length of the exposed surface.

The static-threshold velocity was difficult to determine; however, he found that, once particles began to move, a "dynamic-threshold velocity" lower than the static-threshold velocity would maintain continued particle-movement downwind. He relates this behavior to the action of the particles as projectiles, which upon striking the surface rebound and continue their movement downstream or initiate the movement of one or more particles upon striking the bed. For uniform sand, he found the dynamic-threshold velocity, u_T, in cm per second, to be given by the relation

$$u_T = 0.47\sqrt{(\rho'/\rho)gd}\ \log_{10}(30k'/d) \tag{4}$$

where ρ' is the effective sand-density and k' is the new focus of the velocity-distribution curves obtained from (1) when the flow is carrying particles. For all nearly uniform sands, Bagnold found k' to have roughly the same value, 0.3 cm. For sands of mixed grain-size, according to measurements taken with the natural wind, k' had a value of about one cm. Bagnold's results obtained with uniform quartz sand are reproduced in Figure 10 (note that V_* corresponds to U_*).

According to (1) the dynamic-threshold velocity can also be written in the form

$$u_T = 5.75\,U_*\,\log_{10}(30k'/d) \tag{5}$$

where $U_* = \sqrt{\tau/\rho}$, known as the friction-velocity, z is replaced by k' and k by d/30. Then the friction-velocity required to initiate movement can be solved for from (3) and (4).

$$U_* = (0.47/5.75)\sqrt{(\rho'/\rho)gd} \tag{6}$$

Bagnold gives for his quartz sand $U_* = 120\sqrt{d}$ cm per second, which is plotted in Figure 11 together with his experimental points. For particles smaller than about 0.01 cm, the friction-velocity required to initiate movement was found to increase with decreasing particle-size.

Chepil and Milne found that soil-particles up to 0.8 mm in diameter, making up a smooth, thoroughly dry, pulverized summer fallow, began to move when the wind reached a velocity of 13 to 15 miles per hour at a one-foot height.

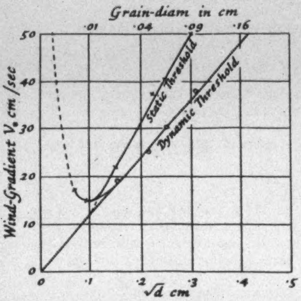


Fig. 11--Friction-velocity required to initiate the movement of sand (According to R. A. Bagnold)

(3) The modes of soil-transport

When a particle is dislodged from the surface by the wind, it moves downstream by sliding, rolling, saltation, or suspension. Bagnold groups the sliding and rolling of particles under the term "surface-creep," which, he states, is brought about by the impact of particles descending from saltation. Saltation is a term used to denote the jumping or bouncing movement of particles within a layer close to the bed. The differences between surface-creep and saltation are gradual, and it is difficult to draw a fixed dividing line between them. The mode of transport a particle will follow will depend on its physical characteristics and on the velocity and turbulent structure of the wind.

In the case of sand-storms, as observed by Bagnold in the Lybian Desert, the height of the visible cloud rarely exceeds five feet, so that, he asserts, all the particles are moving by surface-creep and saltation. Sand-storms of this type occur when the surface is practically free of dust. Measurements in the Egyptian Desert showed that surface-creep amounted to approximately one-fourth the sand-flow in saltation.

Chepil and Milne made measurements of the heights reached by particles in saltation in the open field over loam soil, when the wind-velocity ranged from 15 to 22 miles per hour. Soil-collectors that caught all but some of the finest particles were placed at various heights. These fine particles constituted a small percentage of the transported soil. In Figure 12, the relative quantity of soil blown and relative average diameter of particles are plotted against the height above the surface. Only a small trace of soil was caught at a 38-inch height and 93 per cent of the total soil-movement occurred below a height of 12 inches.

The effect of the turbulent structure of the wind on particles in surface-creep and saltation is not definitely known, although Bagnold believes that turbulence plays a secondary role. Transport by suspension, on the other hand, is directly connected with turbulent fluctuations in the moving air.

Wind-erosion of soil, whose composition varies from fine clay and organic particles to larger sand grains, gives rise to all modes of transport, and fine particles in suspension are lifted to great heights. The appearance of the head of a dust-storm can be observed in Figure 13.

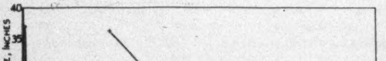


Fig. 12--Approximate curves showing (a) relative quantity of soil blown at various heights over open summer fallow field when wind-speed ranged from 15 to 22 mph at 12-inch height, (b) average diameter in 1/100-mm of soil-particles blown during same period (Measurements of Chepil and Milne)

Von Kármán has made an estimate of the length of time and distance traveled by soil-particles upon being lifted from the surface. Assuming that a particle of mean diameter, d, has the settling velocity, w, given by Stokes' Law

$$w = (2/9)\ (\rho' g d^2/\mu) \qquad (7)$$

and that the root-mean square of the height that a particle reaches in an arbitrary time, t, due to turbulence, is given by the turbulent exchange-coefficient, ϵ, according to the formula

$$h = \sqrt{2\epsilon t} \qquad (8)$$

then, since h = wt, one obtains

$$t = (2\epsilon/w^2) = 81\epsilon\mu^2/2\rho'^2 g^2 d^4 \qquad (9)$$

The range of the particles corresponding to a mean velocity U is given by

$$L = Ut \cong 40\epsilon\mu^2 U/\rho'^2 g^2 d^4 \qquad (10)$$

The results in Table 2 correspond to $\epsilon = 10^4$ and 10^5. The value of ϵ for moderately strong winds lies between those limits, except within the first few feet of the ground, where ϵ decreases as the ground is approached.

Table 2

Diameter of particles, mm	Velocity of fall, cm/sec	Time of flight	Range for 15 m/sec wind	Maximum height
0.001	0.00824	9-90 yrs.	2.5-25 × 10^6 miles	3.8-38 miles
0.01	0.824	8-80 hrs.	250-2,500 miles	200-2,000 feet
0.1	82.4	0.3-3 sec.	150-1,500 feet	2-20 feet

On February 7, 1937, a dust-storm headed northwest from the Texas-Oklahoma panhandle region. Some of the suspended soil--as much as 200 pounds per acre--settled on snow in Iowa, after traveling 500 miles. Analysis of samples taken from the black snow showed that the deposit contained three times as much humus as the best remaining soil in the source-region of the storm.

The presence of transported soil in the air-stream would be expected to alter its usual flow-characteristics, since energy is transmitted from the air to the moving particles. The logarithmic velocity-distribution law is based on the exchange of momentum between neighboring layers of fluid. The solid particles in the flow tend to modify the exchange-process as it occurs in an unladen stream. The alteration in the velocity-distribution by such particles is shown in Figure 10.

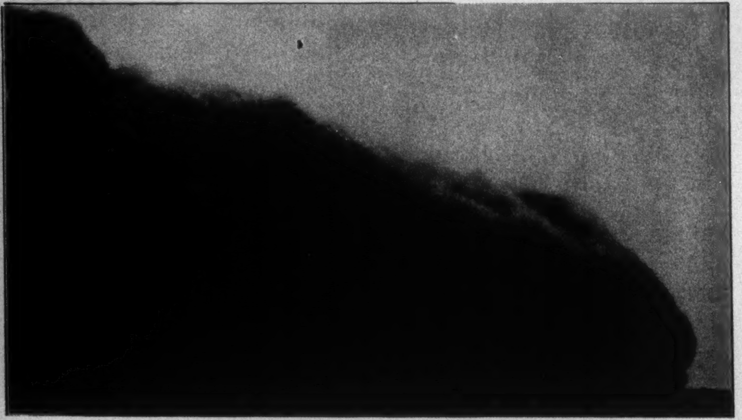


Fig. 13--The "black blizzard" or dust-storm of April 14, 1935
(Picture taken southeast of Lamar, Colorado)

(4) The deposition of transported soil

Soil-particles, upon being lifted from the surface, except the very finest dust that becomes a part of the atmosphere, as elaborated by Blacktin, eventually come to rest again when the wind has subsided or when surface-obstructions alter the velocity-distribution and turbulent structure.

Bagnold has described the following three ways in which particles are deposited from drifting sand:

(a) Accretion occurs when the height-velocity gradient diminishes over a flat surface. Particles drop out and the transport of particles by surface-creep and saltation falls off.

(b) Encroachment occurs when the surface has a sudden drop in slope, as, for example, the lee side of a dune or ridge. The heavier particles in surface-creep roll over the crest into a protected region and accumulate.

(c) Sedimentation occurs in regions where the wind-velocity falls below the threshold value.

In the general case of wind-erosion of soil, transported particles are also deposited around obstructions, such as fences, wind-breaks, buildings, etc., which cause localized changes in the wind-structure. The prevention of the accumulation of transported soil in the form of dunes and drifts offers many problems.

(5) Quantity of soil moved by wind

A number of investigators have measured the quantity of soil moved by wind from sand-surfaces and soil-surfaces of different roughness.

In Table 3 is shown the influence of cultural treatment on the amount of soil blown, as obtained by Chepil and Doughty in a laboratory soil-blowing tunnel. The working section of the tunnel was only six feet long, so that field-conditions were not entirely duplicated. The soil used in the experiments was thoroughly air-dried, and the same structure of the soil was maintained throughout the entire experiment. Dry aggregate structure was determined with a set of sieves ranging from 0.15 to 38 mm in diameter opening.

It is interesting to note that a surface of sceptre clay resisted blowing until high speeds were reached. Bagnold found that movement of Portland cement particles, spread out to form a loose flat surface, could not be initiated by a wind-speed of 50 miles per hour at 10-cm height. The explanation for this phenomenon probably lies either in the presence of large forces of cohesion or in the possibility that the particles are completely within the laminar sub-layer.

O'Brien and Rindlaub, in 1936, published, it is believed for the first time, data on the relationship between the amount of sand transported and wind-velocity. Their measurements were made on Clatsop Beach at the mouth of the Columbia River, which consists of sand with a mean diameter varying from 0.0065 to 0.0085 inch. In Figure 14, the sand-drift, G, in pounds per foot width, perpendicular to the wind-direction, per day, is plotted against the velocity, U_5, of

Table 3--The influence of cultural treatment on the amount of soil blown and on the surface-velocity of wind

(Measurements of W. S. Chepil and J. L. Doughty)

Soil-treatment	Amount in grams in five minutes when wind-speed was 22 miles/hour at 12-inch height			
	Hatton fine sandy loam	Haverhill loam	Cypress clay-loam	Sceptre clay
(a) Level, bare surface	110	215	209	xx
(b) Group of 3 ridges, each 1-1/4 inches high, 7 inches wide, placed at right-angles to wind at windward end of 6-foot length of test area	84	71	170	xx
(c) Ridges as in (b) covering the total surface	75	59	87	xx
(d) Level surface as in (a) with half ton per acre of short straw worked into surface	6	34	17	xx
(e) Ridges as in (c) with straw as in (d)	30	13	12	xx

xx The soil did not blow at this speed of wind. At wind-speed 34 miles per hour, 10.2 grams blew off soil treatment (a) but none blew off the other treatments.

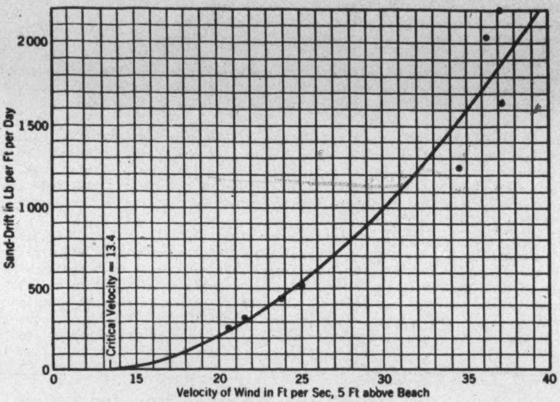


Fig. 14--Relation between wind-velocity and rate of sand-movement
(Measurements of O'Brien and Rindlaub)

the wind in feet per second at five feet above the surface. The smooth curve drawn through the points corresponds to

$$G = 0.036\ U_5^3 \tag{11}$$

for values of U_5 greater than 20 feet per second.

In 1938, Bagnold made measurements of the quantity of sand moving during sand-storms in the Egyptian Desert. He found that, for sand having a mean diameter, d, of 0.025 cm, the quantity of sand transported in metric tons per meter width per hour was given by the relation

$$q = 5.2 \times 10^{-4}\ (u - u_T)^3 \tag{12}$$

where u is the wind-velocity in cm per second at one-meter height and u_T = 400 cm per second is the threshold velocity.

(6) Equipment and experimental methods utilizing an artificially created wind

The experimental methods for investigating wind-erosion can be divided into those utilizing the natural wind in the field and those employing a suitably directed artificially produced air-stream. As stated in the introduction, field-studies have certain inherent advantages and disadvantages. Only within the last few years has the application of an artificially created wind been resorted to as an aid in the attack on the wind-erosion problem. For that reason, the possibilities and limitations of the method have not generally been understood and its usefulness exploited. Therefore, it will be the purpose of this section to discuss at some length this new technique.

The design of an installation for producing an air-stream and correctly directing it is greatly facilitated by the large body of knowledge accumulated in connection with experimental aerodynamics, which has gone hand in hand with the development of aeronautics during the present century.

The installation as used in experimental aerodynamics is known as a wind-tunnel. The main components are the fan, working section, and auxiliary sections for straightening the stream and for increasing the efficiency of converting the energy-input to the fan into kinetic energy of the stream in the working section.

The following three types of wind-tunnel, classified according to the action of the air-stream, have been developed:

(a) Working section on the downstream side of the fan
(b) Working section on the upstream or suction side of the fan
(c) Air-stream circulated around a continuous, closed circuit

All three types have been used in the study of wind-erosion, and their component parts will be discussed in connection with the installations that have been constructed. To distinguish the installation from the wind-tunnel, the term soil-blowing tunnel will be used.

Soil-blowing tunnels can be further classified as laboratory and portable. A laboratory soil-blowing tunnel is a permanent unit constructed to give the optimum possible control over the characteristics of the air-stream and test setup. A portable soil-blowing tunnel is a simplified unit of lightweight construction suitable for use in the field. Its component parts can be dismantled in a short time and transported on a trailer.

The laboratory soil-blowing tunnel--In order to simulate full-scale wind-erosion phenomena in a tunnel, it is necessary that the air-stream have a velocity-magnitude and distribution and turbulence-structure similar to the natural wind near the ground, and that the working section be large enough to minimize wall-interference. Velocity-profiles measured in an open-top channel and a rectangular working section are compared with the logarithmic velocity-distribution of the natural wind in Figure 1. The velocity-range of the tunnel should extend from about five miles per hour to a maximum of at least 40 miles per hour, and in this range the speed should be easily controlled. The flow through the working section must be uniform and the turbulence-level with smooth walls should not be in excess of one per cent.

The minimum dimensions of the working section have not yet been definitely determined, especially the length downstream required to simulate certain soil-blowing conditions. According to Bagnold's measurements with uniform sand varying in diameter from 0.18 mm to 0.3 mm at speeds only slightly above the threshold value, an exposed surface 30 feet in length was required before the sand-flow reached an equilibrium value.

The height of the working section, that is, the distance from the soil-bed to the ceiling should be not less than about 18 inches and preferably greater, for particles in saltation have been found to bounce as high as 50 to 100 times the grain-diameter. In determining the width of the working section, it must be noted that measurements should only be carried out in that portion of the working section in which the mean velocity-distribution is two-dimensional. This condition is not met in the boundary-layers adjacent to the side walls. Therefore, the width of the working section must be sufficient to produce a zone of uniform transverse velocity-distribution, whose minimum width equals the desired width of the test setup. Due to the growth of the boundary-layers on the walls, this minimum width is reached some distance downstream from the entrance.

In Figure 15 is shown a vertical elevation of the laboratory soil-blowing tunnel constructed at the California Institute of Technology by the Soil Conservation Service. The tunnel is a modified Eiffel type with the working section on the suction side of the fan. The component parts of the installation, indicated on the Figure, are the honeycomb, entrance, working section, diffuser, settling box, aspiration-chamber, and propeller-motor combination. Recently a diffuser section of sound-proofing material was added on the downstream side of the propeller to reduce the noise-level.

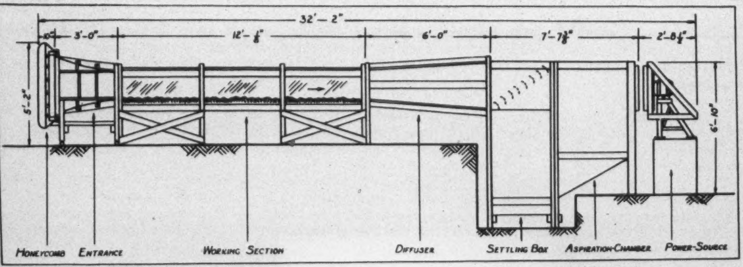


Fig. 15--Vertical elevation of the laboratory soil-blowing tunnel of Soil Conservation Service at California Institute of Technology

Fig. 16--View of working section and traversing and velocity-measuring instruments

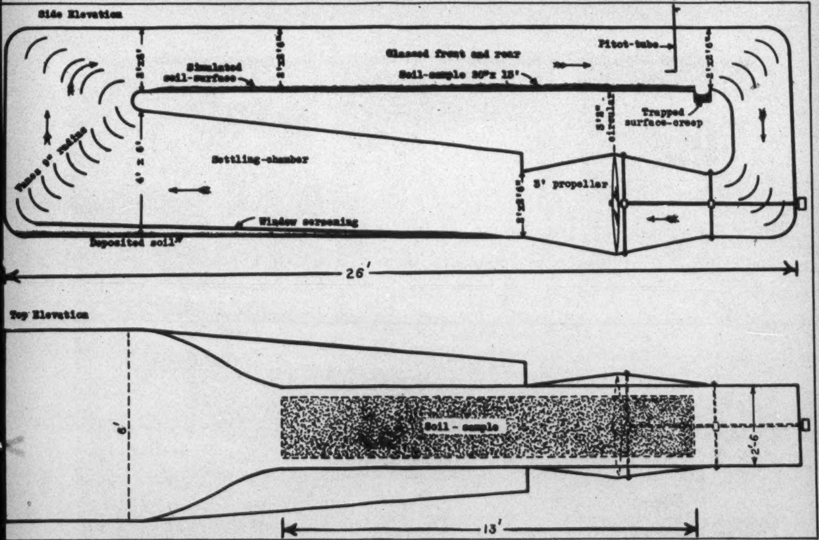
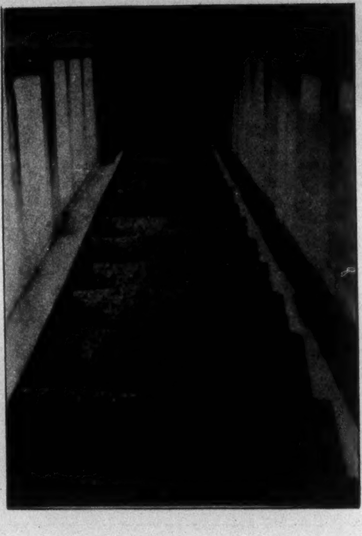
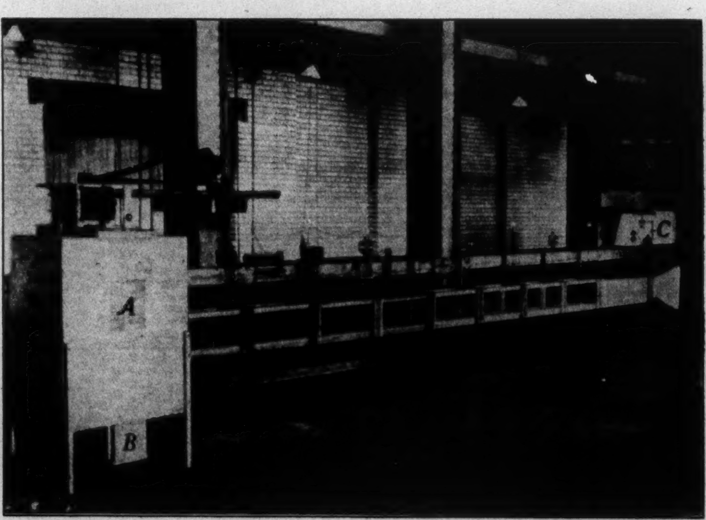

Side Elevation
Simulated soil-surface
Glassed front and rear
Soil-sample 30"x 13'
Pitot-tube
3'11"
2'11'6"
2'11'6"
Trapped surface-creep
3'3" circular
Vanes 9" radius
4' x 6'
Settling-chamber
3' propeller
2'11'6"
Window screening
Deposited soil
26'
Top Elevation
6'
Soil - sample
2'-6
13'

Fig. 17--Vertical elevation and plan of laboratory closed-circuit type soil-blowing tunnel, Soil Research Laboratory, Dominion Experimental Station, Swift Current, Saskatchewan, Canada




A
B
C

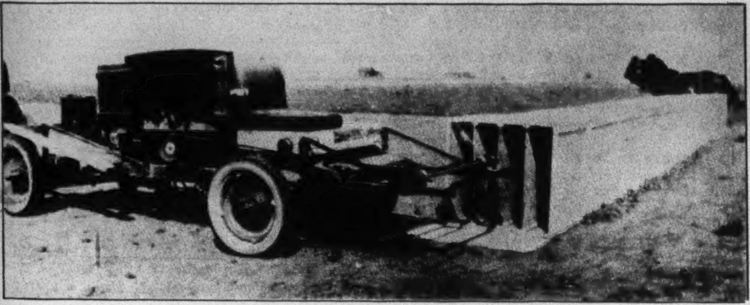


Fig. 20--View of portable soil-blowing tunnel constructed at Soil Research Laboratory, Dominion Experimental Station, Swift Current, Saskatchewan, Canada

by a throttling door between the propeller-tube and the aspiration-chamber. A speed range of 5 to 43 miles per hour can be obtained.

A laboratory soil-blowing tunnel of closed-circuit type is in use in the Soil Research Laboratory, Dominion Experimental Station, Swift Current, Saskatchewan. In Figure 17, an elevation and plan of the tunnel is shown. The working section, shown in Figure 18, with a soil-sample ready for testing, is 2-1/2 feet wide, 2 feet high, and 13 feet long. Wind-speeds up to 35 miles per hour can be obtained. Investigations carried out in the tunnel have shown that soil-blowing as encountered in the field can be satisfactorily simulated.

Bagnold, in carrying out his studies on the transport of desert sand by wind, used a tunnel with the working section on the suction side of the fan (see Fig. 19). This section was one foot square and 30 feet long. The length of the tunnel was constructed of ten units, joined together and supported at the joints by spring-balances. The rates of sand-removal and deposition in any section could, therefore, be measured by direct weighing. A maximum speed of approximately 50 miles per hour was made available.

The portable soil-blowing tunnel--Since soil-factors vary to such a great degree between areas in the wind-erosion regions, it has been found desirable to develop a wind-machine for use in the field. By the aid of this device, the fundamental relations discovered in the laboratory

Fig. 21--View of power-unit and propeller used in the portable soil-blowing tunnel of Soil Conservation Service, College Station, Brookings, South Dakota tunnel for the prediction of the behavior of soil-surfaces exposed to wind can be correlated with particular soil-conditions.

Portable soil-blowing tunnels, thus far constructed, have been greatly simplified in design, at times to such a degree that the value of the results obtained have been appreciably reduced. The most convenient type of tunnel for this application is one with the working section on the downstream side of the fan, for, with this type, the wearing of the fan by particles in the air-stream need not be contended with.

To minimize the weight of the unit for transportation, only a rudimentary honeycomb is used and the converging entrance section has been eliminated. For that reason the rotation of the slip-stream has not been completely eliminated and both the vertical and transverse velocity-distributions have irregular characteristics.

It is believed that a lightweight unit can be built without sacrificing the advantages of a controlled air-stream, limited only by the fluctuations induced by the variations in velocity of the natural wind.

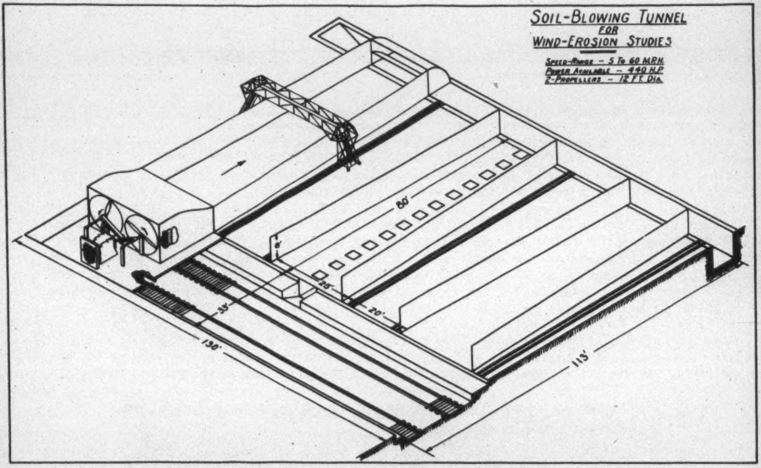

SOIL-BLOWING TUNNEL
FOR
WIND-EROSION STUDIES
SPEED-RANGE - 5 TO 60 M.P.H.
POWER AVAILABLE - 440 H.P.
2-PROPELLERS - 12 FT. DIA.
80'
6'
25'
20'
35'
130'
115'

Fig. 22--Layout showing general view of proposed semi-permanent soil-blowing tunnel

The portable soil-blowing tunnel in Figure 20 has been constructed at the Soil Research Laboratory, Dominion Experiment Station, Swift Current, Saskatchewan. The air-stream is created by a 42-inch propeller driven by an automobile engine. The stream enters the working section through a section four feet long, provided with three vertical baffle-boards. The working section is three feet wide, 3-1/2 feet high, and 44 feet long.

A similar portable tunnel has been designed and constructed by C. C. Joy of the Soil Conservation Service at College Station, Brookings, South Dakota. The power-unit used is shown in Figure 21. A second portable unit is being constructed by the Soil Conservation Service Station at Amarillo, Texas, under the direction of Dr. C. J. Whitfield.

A semi-permanent type of soil-blowing tunnel (Fig. 22) for large-scale investigations has been proposed by Dr. Theodor von Kármán and the present author. The installation is designed to enable shipment of the parts from one soil-blowing area to another.

Instruments--The study of the wind-erosion process has brought forth the need of specialized techniques and instruments for determining the significant quantities involved. Experiments involving transport of soil near the surface must be carried out rapidly, for the surface is continually undergoing change and, furthermore, the surface is sensitive to the presence of any device that in any way alters the normal flow-pattern of the air-stream.

In an unladen air-stream, the mean-velocity distribution and the turbulent structure can be determined with instruments developed in experimental aerodynamics, such as the pitot-static tube for the mean speed, and the hot-wire anemometer for the turbulent fluctuations. The feasibility of measuring the turbulence-structure in a laden stream by means of a hot wire has not been decided definitely since, at least in the case of sand-particles, the fine wire is broken by the impacts of the grains.

One of the important phases of wind-erosion for which experimental data should be obtained is the distribution of burden carried by the air-stream above the surface. As far as is known, no accurate method of measuring the density of this flow has been worked out. Soil-traps have been found not very satisfactory, since they catch practically no suspended fine particles and they disturb the flow appreciably. The use of a photoelectric cell to measure the absorption of light in a light-beam, and the pumping of air through a sampling tube at the same rate prevailing at the measuring point in the laden air-stream are two methods that have been proposed for trial.

The wind-erosion problem has not yet required any new techniques or instruments for determining the physical characteristics of soils, or the aerodynamic properties of obstacles.

(6) Windbreak experiments in a wind-tunnel

The usefulness of obstacles of various kinds in combating wind-erosion has long been appreciated. Recent dust-storms on the Great Plains originated because the surface, once overgrown with a protective vegetation, is now largely denuded. When land in this region is clean-tilled or overgrazed and the original protective layer destroyed, the ingenuity of man is required to replace it by equally efficient guardians.

On the basis of the discussion in the preceding sections, it can be concluded that if soil subject to wind-erosion must be exposed to prevent the initiation of soil-movement, the velocity near the exposed surface should be reduced to a minimum possible without increasing the turbulence-level of the air-stream. To reduce the velocity of the wind near the ground the kinetic energy in the moving air must be dissipated or the wind deflected upward.

In the practical problem of wind-erosion control over large areas, some of the most suitable obstacles are to be found in tree and hedge windbreaks and close-growing tall grass-barrier strips. In laying out windbreaks, information is needed on the arrangement of planting that will protect the largest possible area. A number of field-investigations have been conducted in this and other countries to determine the above characteristics and also the effect on the productivity of land.

This section will contain some unpublished results of wind-tunnel tests on windbreaks, carried out at the Guggenheim Aeronautical Laboratory of the California Institute of Technology by J. S. Atsumi in 1936 upon the suggestion of Dr. Th. von Kármán.

The experiments were made in a suction-type wind-tunnel (Fig. 23), with a working section 30 inches deep and 9-9/16 inches wide, at wind speeds of 65 miles per hour. Model trees, one inch in height, made of 3/4-inch cotton balls, through which nails were stuck leaving 1/4 inch between the tunnel wall and the cotton balls were used. Various arrangements tested are shown in Figure 24. Identical arrangements of the model trees were installed on both walls of the working section, in order to assure a similar type of air-flow over both walls.

The Reynolds Number of the experiment corresponds to a value of 5×10^4; whereas, in full scale for 30-foot trees and a wind-speed of 30 miles per hour, a value of 8.5×10^6 is obtained. Studies of the drag of spheres with a rough surface show, however, that the drag-coefficient practically is independent of the Reynolds Number; therefore, the model tests should not be greatly in error.

Velocity-surveys were made with a pitot-static tube in the center of the working section, from midstream to within 1/16 inch of the wall, at various stations downstream.

In Figure 25 are plotted velocity-distributions (u_w/u versus z/H) at a station four times the height, H, of a tree downstream of the rearmost trees in the arrangement. The pitot-static

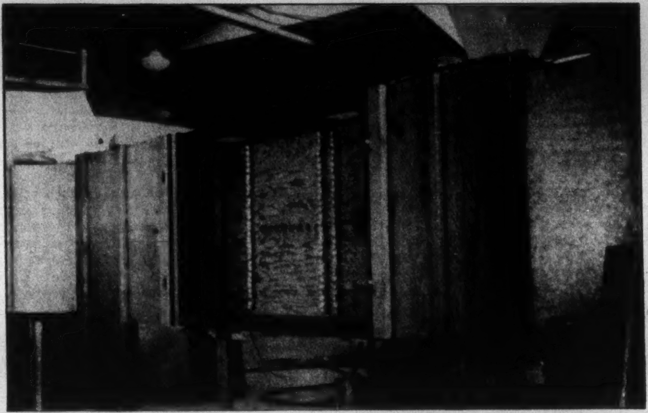


Fig. 23--View of working section with windbreak arrangement installed on one wall

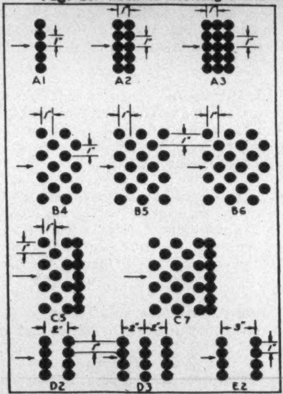


Fig. 24--Arrangement of model trees tested in windbreak experiments

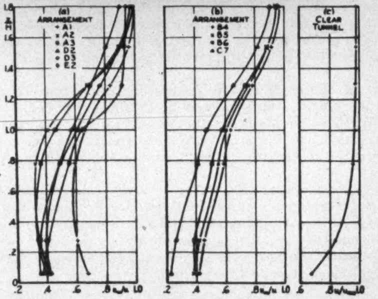


Fig. 26--Velocity-contour map in a vertical plane downstream of arrangement A-2

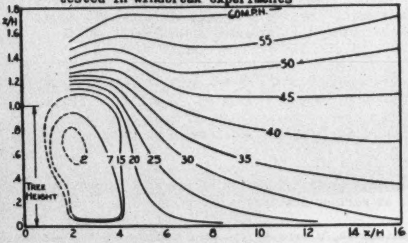


Fig. 25--Velocity-distribution curves, measured at $X = 4H$, for various arrangements are shown in (a) and (b) and in a clear tunnel in (c) [$u_{max} = 65.5$ mph] tube was located in the gap between two trees in the last row. In Figures 25 and 26, the following notation has been used: u = local mean air-speed in a clear tunnel; u_w = local mean air-speed at corresponding points, with windbreak arrangement installed; u_{max} = maximum mean air-speed at center of the working section = 65.5 miles per hour; χ = distance downstream from rear row of windbreak; z = distance above surface; H = height of tree.

Table 4

Arrangement	$(1 - u_w/u) \times 100$ at $z = H/5$, $\chi = 4H$	No. of trees per 4H width	Shielding effectiveness per tree
A-1	37	4	9.3
A-2	63	8	7.9
D-2	60	8	7.5
E-2	60	8	7.5
B-4	56	8	7.0
B-5	60	10	6.0
D-3	65	12	5.4
C-7	75	14	5.4
A-3	64	12	5.3
B-6	62	12	5.2

To compare the shielding effectiveness of different arrangements, the values for the wind-velocity reduction in per cent for $z = (1/5)H$ and $\chi = 4H$ were chosen from Figure 25, and these values were divided by the number of trees per unit-length of the windbreak. Shielding-effectiveness values per tree for the various arrangements are shown in Table 4. It is seen from Table 4 that arrangement A-1 gave the greatest shielding effectiveness per tree. However, the windbreak used in this arrangement reduced the velocity the least at a station a distance equal to 4H. The windbreak with arrangement A-2 gave great shielding per tree as well as per windbreak.

Since arrangements A-1, A-2, and D-2 gave the highest shielding-effectiveness values, wind-velocity surveys were made for these arrangements at stations downstream as far as 16 times the height of a tree. A velocity-contour map in the vertical plane downstream of arrangement A-2 is drawn in Figure 26. (The velocity-contours should not be confused with stream-lines.)

The decrease of wind-velocity, due to the various arrangements, became almost the same when the distance downstream exceeded 6H. If a 50 per cent decrease in velocity of the free wind is chosen arbitrarily as the maximum required at $z = (1/5)H$, then a windbreak of arrangement A-2 must be followed by another similar windbreak at a distance of about 12H to protect the soil-surface beyond that point.

A closer study of the velocity-contours plotted in Figure 26 shows that actually, as the ground was approached below (1/10)H immediately to the lee of the trees, the wind-speed again increased, because the space between the trees permitted excessive wind-penetration. Such penetration can be reduced in an actual windbreak by planting bushes or grass between the trees. It should not be concluded, however, that it is desirable to eliminate penetration. On the contrary, preliminary model-tests demonstrated the superiority of tree windbreaks to solid fences of the same heights.

Conclusion

In this survey, an attempt has been made to review the present status of the dynamics of wind-erosion from the viewpoint of the soil conservationist, in whose hands lies the responsibility for preventing the destructive effects of the process. The solution of the problem is dependent on a program that correctly balances the progress made in theoretical studies and laboratory investigations of the underlying principles of wind-erosion with the development of practical methods incorporating the adjustments required to meet the aspects of the problem as they are encountered in particular situations under actual conditions in the field.

There is available only a rudimentary understanding of the basic mechanisms that need to be investigated and interpreted before a generally useful body of theory can be developed for predicting the behavior of soil-surfaces exposed to wind. Studies will require a careful breakdown of the many factors that play a part into significant groupings before their effects can be determined. Furthermore, in these studies it is of great importance that all the variables entering into the experiments be known and controlled.

The most satisfactory way of meeting these conditions appears to be through the application of an artificially created air-stream in a soil-blowing tunnel.

The design-criteria for laboratory tunnels suitable for blowing soil and for model-studies have not been definitely decided, for example, the length of soil-surface that must be exposed and the height of the working-section ceiling above the surface required to simulate actual conditions. Tunnels so far constructed are, however, satisfactory for qualitative evaluations.

The development of instruments for measuring wind-structure and the distribution of carried particles needs to be accelerated. The technique for determining the turbulent characteristics of an unladen air-stream has been worked out, but the equipment is available only in a few aeronautical laboratories. A device for measuring the density of a soil-laden air-stream, within layers very close to the surface, is needed in conjunction with analyses of the formation of surface-markings, such as ripples.

The advantages of laboratory tunnel investigations of models of obstructions and surface-formations are only beginning to be realized. For example, the cumulative effect of a series of windbreaks, spaced at different distances downstream, the effect of departing from straight-line planting of windbreaks, and the most efficient method of utilizing the natural wind to disperse sand-dunes are typical problems that lend themselves to model-studies.

The mechanism underlying the formation of dunes has long been sought. Bagnold found that small-scale experiments in his tunnel with a sand-surface of varying texture gave results that might possibly explain dune-formations. This work needs extension.

Qualitative interpretations of the results obtained with models can easily be drawn; however, quantitative evaluations are awaiting the establishment of similarity laws for air-flows carrying granular material and for models mounted within the boundary-layers of a flow over a surface.

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DISCUSSION

TH. VON KÁRMÁN (California Institute of Technology, Pasadena, California)--I sincerely regret that I cannot personally attend this important symposium initiated by Dr. Lowdermilk. I feel that the problems reviewed in the symposium are of equal significance for immediate practical applications and for the development of our basic scientific knowledge.

Sediment in water and dust in air have been the subjects of numerous investigations and more or less speculative theories in the past. However, recent progress in fluid mechanics gives the hope for more systematic and quantitative understanding of the phenomena and for the establishment of methods leading to "engineering calculation" of protective structures and measures replacing pure "rules of thumb."

The main difficulty in the theoretical treatment of erosion-phenomena, that is, of entrainment, transportation, and deposit of dust and sediment, is the random character of such processes. The random character of wind-motion is evident also to the casual observer, because of the large size of the air-masses, whose interactions constitute what we call "atmospheric turbulence." The same applies to some extent to a river, whereas in the case of pipe- and channel-flow closer observation and instruments with small time-lag are required to investigate the fluctuating character of the motion.

The progress in the last two decades in better understanding of turbulent motion consisted essentially of the following points:

(a) Systematic experimental investigations on the distribution of the mean velocity in pipes, channels, rivers, and in the natural wind--the mean velocity being defined as time-average of the fluctuating velocity at a fixed point of the flow.

(b) Development of a theory for such velocity-distributions, which has resulted in mathematical expressions for the velocity-distribution as function of the ground-friction (propulsive force) and some roughness-parameters of the ground. These formulas are so far semi-empirical and they contain certain numerical constants derived from experiment; however, these constants have a universal character.

(c) Development of a theory for the laws of turbulent exchange, which can be applied to transfer of heat and matter in turbulent flow.

(d) Experimental and theoretical investigations on the statistical laws governing the generation and decay of turbulence.

The application of the new knowledge has led to a theory of distribution of the concentration of small-size sediment in a fluid. This theory is based on the conditions of a statistical equilibrium between the random forces of turbulence and the force of gravity. It seems that this theory is a useful guide for the interpretation of experimental results, but its application is restricted for the following reasons:

(a) It neglects the influence of the sediment or dust load on the velocity-distribution in the river or the wind.

(b) It does not allow any conclusion as to the maximum concentration which the fluid can carry.

It appears that one of the most imminent problems is the further development of the basic theory to include these two important points, which probably are closely connected, since very likely the saturation is determined by the diminishing effect of the sediment on the turbulence of the flow.

Further objectives of the basic scientific investigation are, in my opinion, the following items:

(a) The problem of the limiting value of the velocity or shearing stress at the ground which determines the entrainment of particles in the turbulent flow.
(b) Correlation of the roughness-parameters used in the theory of turbulent flow with the geometrical parameters of the actual ground or cover.
(c) The probability or statistical law of the motion of heavy particles moving by saltation or otherwise.
(d) Physical explanation of periodical formations of sediment deposit observed in a great number of cases; both in water-flow and in wind, for example, riffles normal or in the direction of the main flow.

Some of these problems have been subjects of extended experimental investigations both in this country and abroad in the past. Also, promising attempts have been made for theoretical interpretation of the results.

I believe firmly that:

(1) The solution of these basic problems will be found by cooperation of theory, laboratory experiments, and field-observations.
(2) Their solution will greatly benefit the practical applications, that is, the economical and efficient design of structures and protective measures in the field.

I certainly hope that the excellent review of Dr. Malina on problems related to wind-erosion will give an impetus to fill the gaps, which I have tried to indicate in this short discussion.

H. H. FINNELL and CHARLES J. WHITFIELD (Soil Conservation Service, Amarillo, Texas)--To the soil conservationist, a clear understanding of how and why soil-movement occurs and the relation of such factors as soil-, cover-, and tillage-practices to the process is essential to the development of adequate control-measures. Wind-erosion investigations may be classified roughly into three groups.

First, the mechanics of wind-erosion, that is, the study of the principles of dynamics responsible for soil-drift. Some of the problems that need studying in this connection are: (a) Wind-velocity, its variation at different distances from the ground surface, direction, duration, and the nature of the turbulence in air-currents of different velocities; and (b) properties of soil-particles that make them susceptible to movement--size, diameter, shape.

Wind-erosion has been the subject of much discussion during the past several years. Considerable agreement exists as to the general causes and as to methods of reducing the blow-hazard, but only recently have the actual processes involved been investigated. Studies on turbulence in the wind, the initiation of the movement of soil-particles, the nature of transport-suspension, saltation, surface-creep, distance transported, and the deposition of transported material are essential to dealing intelligently with wind-erosion problems. When these are known and can be interpreted in relation to the effects of agronomic practices on soil-structure, a definite step forward in agricultural progress will have been accomplished.

Second, a study of the causes of accelerated wind-erosion, including such factors as the destruction of the vegetal cover, residues, and soil-structures by cultivation, drought, or heavy grazing. Research is badly needed to determine the effects of cultural practices on susceptibility of soils to wind-erosion. Data are needed on the mechanical composition of the soil--its firmness of bonding, the amount of potential abrasive that it contains, its reaction to wetting and drying, to freezing and thawing, and its perviousness.

Acceleration of erosion by wind may be mainly a process of abrasion by the wind-driven particles initially loosened. This appears to be the case for Pullman clay-loam, the predominate soil-type on the Amarillo Experiment Station. Observations and field- and laboratory-analyses indicate that the breakdown of protective clods takes place through the action of wetting and drying, freezing and thawing, and possibly the mechanical action of raindrops. Coupled with cultivation-practices, this produces small clods somewhat less than two mm in diameter. Wind-movement strong enough to roll these clods causes further breakage into particles less than one mm in diameter. These smaller particles or aggregates ranging in size from 0.2 mm to one mm are quite stable to further size-reduction and are comparatively hard. Wind-velocities greater than 12 to 15 miles per hour near the ground-level cause these aggregates to roll along the surface. Wind with a somewhat greater velocity actually picks up these aggregates and carries them along close to the surface for several feet with a bouncing action. Such hard particles act as an abrasive agent and break down clods forming more of the small aggregates which in turn break down more clods. Although these particles are quite resistant to breakage, they grind themselves into smaller and smaller units until they become light enough to remain suspended in the air. They are then of little importance from the standpoint of causing additional erosion. This tends to explain why such erosion often starts on one small, poorly protected area and spreads rapidly. These aggregates thought to be responsible for wind-erosion appear to remain intact within the soil-mass for some time. Thus, soil that has suffered from wind-erosion in past seasons is much less resistant than soil that has not suffered from such erosive action.

Third, are wind-erosion-control methods and the testing on a field-scale of various practices designed to control soil-drift. Such cultural methods as a rule will be based on both field-experience and the knowledge developed from studies dealing with the fundamental causes of wind-erosion.

From the viewpoint of practical application in the field, wind-erosion-control measures must be classified according to the character and duration of their effectiveness. The character or the mechanics of the measure determines its applicability to a given condition, while the duration of the erosion-resisting effect determines the time or economic value of the measure.

While most of the emergency efforts toward wind-erosion control are concerned with the behavior and management of individual soil-particles after they have been dislodged upon the surface, the more economical and at the same time the physically more effective measures are concerned with the behavior and control of the surface-exposures both before and after the dislodgment of individual particles. Although the control-measures that produce semi-permanent effects resulting in surface-exposures resistant to the dislodgment of particles are of the greatest importance in conservation farming and range-management, the most interesting problems in the dynamics of wind-erosion undoubtedly involve the behavior and control of soil-particles already dislodged, or in imminent prospect of dislodgment, and subject to free surface-movement.

The practical measures that are available for the control of soil-grains and small aggregates partly constituting the surface-exposure of soil and thus subject to atmospheric factors, including wind, may well be considered under two separate type-classifications.

First are the practices that add to or modify the micro-structure of the surface-exposure, providing tiny zones of lodgment that either shelter or becalm individual soil-grains. Under this heading might be mentioned such factors as cracks, clods, small tillage-furrows, mulches, low-growing vegetation, sparse or dense, and the trashy residues of previous vegetation.

Second are the practices that affect the macro-structure of surface-exposure providing relatively extensive zones of lodgment which becalm considerable surface-areas of soil. Under this heading might be mentioned such factors as ridges, border-plantings, strip-crops, shrubs, trees, or shelterbelts, and many kinds of wind-breaks, including fence-rows.

Either type of structure may be effective in preventing removals of soil from the protected area, but they vary greatly in their desirability from the standpoint of duration of effectiveness and the possible results of excessive accumulations from adjacent eroding areas. For example, the protective micro-structure of a cloddy surface may be equally as effective in preventing erosion as a short dense stubble, but usually cannot be depended upon to endure through an ordinary blow-season. All these types of protective surface-structures have given capacities of accumulation that may be beneficial, neutral, or harmful in effect upon saturation and that, when smoothed over by accumulations, may continue to protect the covered soil with more or less relative permanence, although unobstructed movement of accumulated debris goes on above the original protective structure.

Experimental technique is badly needed in the study of wind-erosion. Attempts are being made on the Amarillo Soil Conservation Experiment Station to develop a method whereby the cloddiness of the surface-soil may be expressed in such a quantitative manner that the probable resistance to wind-erosion of a particular area may be predicted. The development and use of both laboratory and field blowing-tunnels as a method in studying the mechanics and causes of soil-drift are necessary, since somewhat greater control is needed than is possible under usual blowing conditions in the field. Aside from the development of the aerodynamics theory, a necessary basis for the further understanding and refinement of our technique, the portable soil-blowing tunnel can be of great use as an implement to test out the relative value of various field-methods of handling tillage and crop-residue disposal under severe field-conditions. It has been found that what might be considered desirable surface-conditions vary greatly in duration and effectiveness under different combinations of soil-type and degree of erosion. The soil-blowing tunnel should very quickly and very greatly increase our fund of specific information applicable to critical areas.

DYNAMICS OF WATER EROSION ON LAND-SURFACES

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(A joint contribution of the office of Research of the Soil Conservation Service and the Ohio Agricultural Experiment Station)

Method of approach

Soil-erosion caused by rainfall and runoff and the transportation of sediment by surface-runoff, of necessity, have been studied in an empirical manner because of the complexity and extent of the problems and the need for the development of useful working formulas from a limited supply of data. Empirical formulas are generally restricted in their application, even within the range of the experimental data upon which they are based. Yet such formulae often are extrapolated beyond the limits of their validity.

Solution of soil-erosion problems, based on purely rational methods, would require many simplifications for a rigorous mathematical treatment. For the present, a combination of empirical and rational methods seems desirable. Correlation of the process of rational analysis with experimental observation permits evaluation of the factors in more or less the order of their importance and reduces the number of data necessary to the purely empirical approach.

Too frequently the physical processes of erosion have been related to groups of factors with little regard as to whether the resultant processes are directly or indirectly dependent upon the separate causal factors. Rational methods may be advanced in an approach that systematically organizes the factors and rationally relates them to the processes involved.

In this paper an attempt is made to point out the factors upon which the surface-movements of water on a watershed are directly dependent, the forces exerted by these water-movements, the physical processes of erosion resulting from the forces, and the resistance of soil and vegetation to the movements and forces. Experimental results and field-observations taken from many sources that emphasize important considerations are summarized.

Climate

The major climatic factors affecting surface-water movements and resulting erosion-processes are precipitation and temperature. Attention is directed to the characteristics of the water delivered to the ground-surface in the form of direct rainfall or as rainfall modified by the vegetal cover, and to the effects of temperature on infiltration, and to the depletion of soil-moisture by such processes as evapo-transpiration and percolation.

Surface-water movements

The characteristics of water delivered to the ground-surface are directly dependent upon the distribution, intensity, and amount of rainfall, and the type, amount, and distribution of vegetal cover. The amount of water delivered to the ground-surface in excess of temporary surface-storage and infiltration determines the amount available for surface-runoff. Contributions by seepage, spring-flow, and other sources are recognized, but for purposes of this paper require no detailed discussion.

The distribution, depth, and velocity-distribution of the water available for surface-runoff are determined by physiographic factors, ground-surface conditions, and vegetal cover. The physiographic factors include area, shape, slope, drainage-pattern, and drainage-channel characteristics. The shape of a given watershed determines the areal distribution of the water available for movement. The drainage-pattern as used above defines the natural distribution of all depressions over the watershed where flow is determined principally by channel hydraulic characteristics. This pattern serves to describe the relative position of the major drainage-channels with respect to the runoff-contributing subareas where flow-characteristics often may be determined primarily by surface-resistances. The routing and development of flow in the channel-system are influenced by the location of confluences as shown by the drainage-pattern, the hydraulic characteristics of the channels, and the flow-characteristics of the water delivered by the subareas.

The literature records considerable information on water-movements in channels but little on the characteristics of flow over the ground-surface. The early contributions of Ramser [see 1 of "References" at end of paper] are outstanding in the field of surface-runoff from agricultural areas. Horton [2], Horner [3], Sherman [4,5], and others have contributed to the advancement and thinking concerning surface-runoff phenomena, essentially through analysis of hydrographs.

Formulas and methods developed by Horton [6,7] and others have been applied by numerous investigators to the analysis of small-plot hydrographs in an attempt to determine relationships of the various factors involved. "M" in Horton's surface-flow equation expresses the relationship between surface-detention and rate of runoff and reflects the type of flow, whether turbulent, partially turbulent or laminar, or subdivided.

Erosive forces of surface-water movements

Rainfall-impact--The force exerted by the impact of raindrops is dependent upon the intensity of rainfall and the size of the drops. The momentum acquired by raindrops is the product of their mass and velocity and the impact exerted is that resulting from the loss of momentum. If velocities were constant during uniform rainfall-intensities, total impact per unit of area should be the same regardless of drop size. Large drops, however, concentrate the pressure at fewer points.

Neal [10] found that the velocity of drops became approximately constant after about two seconds from the time they had started to fall. Consequently the difference in momentum after this time is essentially a function of their mass. Large drops by presenting less surface to atmospheric resistance than an equivalent volume made up of small drops acquire greater velocity and consequently greater momentum.

Drops approximately equal in size to the larger drops of natural rainfall measured by Bentley [47] were observed to acquire in a distance of 3.5 feet more than one-half the impact of similar drops falling a distance of 28 feet [10].

Recently Laws [11] has conducted extensive laboratory studies of the characteristics of raindrops produced by artificial-rain applicators. Drop-size was measured by a modification of Bentley's technique; drop-velocities were determined by a photographic apparatus. Using an energy/area index to express the erosivity of the raindrops, Laws found that soil-dispersion increased and infiltration decreased with increasing drop-size and velocity of fall.

Impact of raindrops is important for consideration, particularly in localities where the rainfall-intensity and size of drops vary with the seasons. Bentley [47] has observed that clouds moving in vertical planes (typical of thunder-storm clouds) usually form large drops, while clouds moving in horizontal strata, either high or low, seldom precipitate large drops. Unpublished data by Borst and Woodburn [12] show that, for a six-year average at Zanesville, Ohio, 32 per cent of the annual soil-losses from fallow-plots occurred in June, while 73 per cent of the losses occurred in June, July, and August. Rainfall is fairly well distributed throughout the year; total runoff is greater in the winter. The high summer soil-losses are probably due to increased impact resulting from higher intensities and larger drop-size, as well as higher rates of runoff.

Soil-dispersion and erodibility--Several processes may contribute to the loosening and dispersion of soil during rainfall. The direct mechanical dispersion and compaction of soil by the beating action of raindrops has frequently been emphasized. Early investigators, particularly Wollny [13], called attention to the dispersive effects of rainfall on soil-structure. Lowdermilk [14] and Hendrickson [15] confirmed Wollny's contention that the dispersion of the soil by rainfall resulted in the clogging of the soil-pores.

When dry soils are wetted some degree of slaking usually occurs. The characteristics of this explosive type of dispersion have been described previously [16]. The process is most violent and complete when dry, unprotected soils are wetted rapidly. Slaking accounts, in part at least, for the relatively high erodibility of certain soils during early stages of runoff [10,17]; the dispersed material is most susceptible to movement.

During the wetting process, hydration of soil-colloids reduces the cohesive power of these materials. The result is a softening of soil-crumbs and clods. Nichols [18] has shown that the cohesion of loose-dry soils first increases and then rapidly decreases as the moisture-content of the soil is increased.

Alternate wetting and drying of most soils is accompanied by differential swelling and shrinkage. The extent to which these processes contribute to soil-structure changes and erodibility has not been evaluated.

Middleton [19] has suggested the dispersion-ratio as an index of the ease with which soil-particles would be brought into suspension by the forces of rainfall and runoff.

Erodibility is a dynamic property or condition of soils that to date has defied direct measurement.

Surface-runoff--The shear or tractive force and the transportive power of surface-runoff are directly dependent upon the hydraulic characteristics of flow. For purposes of this paper flow may be described as fully laminar when it acts as a viscous fluid; partially laminar and turbulent, approaching turbulent as the influence of viscosity decreases; and turbulent when it acts independently of the fluid viscosity and its velocity and direction change erratically and rapidly. The basic knowledge of the theory of turbulence has been presented by Prandtl, von Kármán, Taylor, and others, applied by Shields to bed-load movements in an outstanding pioneer effort, and furthered by Straub, Rouse, Lane, Kalinske, O'Brien, and others [20,21,22,23,46].

Shields reasoned that the initial movement of material would require a certain "critical" velocity at a distance above the bed proportional to the sediment-diameter. He discussed the effect of viscous action on the beginning of movement and expressed the parameters for sediment transport during turbulent flow [21].

Ramser [24] discussed the relationship between velocities, channel cross-sections, and frictional resistances to flow as they may be controlled to reduce erosion and silting from the viewpoint of a "critical" velocity at which no silting or erosion will occur if the water is already fully charged with silt. Little [25] has developed an erosional rating for turbulent flow.

O'Brien, using concepts of atmospheric turbulence, calculated that the distribution of sediment of any size follows a logarithmic law which is a function of the settling rate of particles of that size, the shape of the vertical velocity-curve, and the shear or tractive force at the stream-bottom [46]. Christiansen [26] found silt distributed according to these relations.

Horton [27] has suggested prerequisite conditions of slope, roughness, depth, and velocity for the phenomena of rain wave-train flow. In preliminary work at the Alabama Agricultural Experiment Station on a micro-biologically stabilized, smooth, fallow-plot, rain wave-train flow was observed on all slopes above two per cent [9].

Plant-residues, vegetation, or depression-storage may cause build-up of surface-detention which, when released suddenly, may result in irregular and erosive flow. It is also believed that irregular flow on natural watersheds may occur as a result of repeated build-up of detention-depth by interfacial tension-relations and subsequent release when gravity overcomes the influences of these forces.

The problems of soil and surface-water movements on a watershed are extremely complex. Flow may vary from shallow laminar and subdivided sheet-flow of low turbulence, in which velocities are low and sensibly constant, to rill and channel-flow characterized by extreme turbulence and high velocities, or to the shooting flow that often occurs in gullies. The size, shape, and density of the particles are frequently variable and changes in boundary roughness may be extreme. Little is known about the influence of profile-shapes.

Observations indicate that erosion is due chiefly to turbulent flow, although laminar flow may roll or shove particles. Movement of soil-particles is directly influenced by the condition of water-motion near the ground-surface. The forces exerted by turbulence depend upon depth, velocity-distribution, and soil-surface conditions. Soil-particles are picked up when the upward components of force exceed the settling rate of the particles and they are carried forward by the

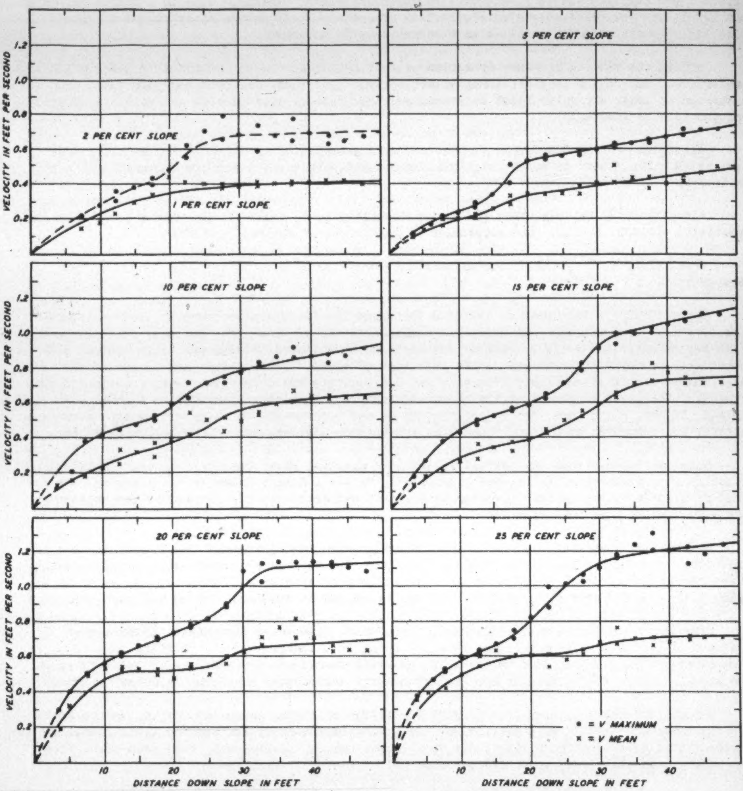

Fig. 1--Mean and maximum velocities of surface-flow on a smooth fallow plot, mechanically tilted to different slopes

forward components. Particles continue to be lifted and transported if the upward components continue to exceed the settling rate.

Through fallow-plot studies, Borst and Woodburn [8] found that average velocity of flow increased exponentially with degree of slope; soil-losses increased exponentially with average velocity. A review of available literature seems to indicate that the erosive power of running water varies approximately as the third power of velocity.

Usually, because of the lack of suitable techniques for direct measurement, velocities of surface-flow have been computed. Velocities thus computed have been average velocities; values obtained have generally been less than 0.5 foot per second and seldom exceeded 1.0 foot per second.

Velocities measured by a salt-velocity method [9] during rain wave-train flow on a very smooth fallow-plot mechanically tilted to different slopes are presented in Figure 1. No erosion occurred although the velocities were higher than those usually computed for plots on which erosion had taken place. The actual depths and velocities causing erosion are believed to be greater than generally computed. These considerations indicate that attention should be given to the distribution, depth, and velocity-distribution of flow over the plot, the development of rills, and the various factors affecting the resistance of soil to erosion.

The authors plan to attempt to measure depth and velocity-distribution of surface-flow on plots and watersheds at Coshocton, Ohio. Consideration will be given to such techniques as the use of the Bentzel tube, pitot-tubes, a hot-wire current-meter, and the salt-velocity method as modified by one of the authors in preliminary studies [9].

There is a dearth of applicable factual information on the hydraulic characteristics of surface-flow, particularly as it relates to erosion. Research results from which rational approaches to the problem may be developed, are most urgently needed. Advances in the knowledge of fluid turbulence as related to entrainment, transportation, and deposition of sediments should be closely followed.

Conservation of rainfall and control of surface-flow runoff and related soil-erosion

In the preceding part of this discussion, surface-water movements and the resulting erosional forces and processes were discussed. Land-use changes and conservation-methods of farming are designed to modify and control these movements, forces, and processes.

Functional classification of control-methods--It is believed that the degree of effectiveness of soil- and water-conservation methods affecting surface-flow is determined by the extent to which they contribute to the attainment of one or more of the following objectives:

(1) Reduction of time and extent of exposure of bare ground to water-erosion, particularly during periods of heavy or intense precipitation--adjustment of vegetal cover and cropping system
(2) Reduction of the force of rainfall-impact--vegetal or mechanical obstructions that deliver water to the ground-surface as non-erosive flow
(3) Reduction of surface-flow runoff through increased infiltration and surface-storage--utilization of plant-residues, cover-crops, sod-crops, contour-tillage, basin-listing
(4) Prevention of excessive concentrations and velocities of surface-flow runoff--vegetal or mechanical obstructions that control surface-flow
(5) Removal of excessive surface-flow runoff by means of water-disposal systems possessing erosion-control hydraulic characteristics--terraces, sodded waterways, meadow-strips, outlet-ditches

In addition to the above, there is another very important objective that should not be overlooked:

(6) Building and maintaining soil-fertility and productivity at levels where vegetation can be produced profitably and safely--maintenance of a sufficient organic-matter supply, a good structural status, and good biological activity in the soil

The true relationship between the last objective and the first five is sometimes misunderstood; the value and frequent necessity of utilizing the first five principles in attainment of the sixth is often underestimated. The last principle is an ultimate agricultural objective, which, once attained and thereafter maintained, is generally conceded to contribute effectively to the other direct erosion-control objectives.

The above classification of processes and objectives is presented as a basis for judging the efficiency of specific soil- and water-conservation practices, which, however, cannot be discussed in detail in this paper. They will be considered briefly according to the sequence of their effect on the land under natural conditions.

Reduction of soil-exposure to climatic forces--Throughout the study of control of water-caused soil-erosion and soil- and water-conservation, it will be observed that "timing" is an important factor. The desirability of considering the climate when planning land-use adjustments of the vegetal cover or cropping system has been pointed out by Baver [28] and others. Under conditions in Ohio approximately 90 per cent of the total annual soil-losses from fallow-land occurred during the summer season [12].

Crop-rotations that protect the soil with close-growing vegetation as much of the time as is practicable, are ideal for reducing the time of exposure of cultivated lands. Such rotations may include legume-grass, sod-crops, winter grains, winter and summer green-manure cover-crops, stubble and stalk mulches, and other plant-residue mulches.

Plant-interception and conservation of rainfall--Field-observations indicate that the physical distribution of vegetation in the zone between soil and atmosphere is probably more important than quantity in determining the delivery characteristics of water to the soil-surface. Relatively small amounts of low, close-growing vegetation or small amounts of plant-residues appear to be remarkably effective, provided that the ground-surface is approximately covered.

It has been found that from 13 to 37 per cent of the total annual precipitation never reaches the ground-surface under different types of forest-cover in various sections of the United States [29].

Maximum quantities of interception-storage by common field-crops of over one-half inch have been reported by Musgrave and Norton [30]. Values ranged from 0.21 to 0.49 inch for corn and from 0.15 to 0.58 inch for alfalfa during four late-summer storms where rainfall was in excess of the maximum storage reported. The above values are of the order of magnitude of those obtained by Clark [31].

Wollny found that from 45 to 88 per cent of the total rainfall reaches the ground-surface directly [13]; the amount of interception was dependent upon both kind and number of plants per unit-area. The major effect of the vegetation was attributed to the protective influence of the cover against the impact of rainfall [32]. No results were found for grasses or close-growing, legume-grass hay-crops.

Practically no direct information is available on the influence of type, amount, and distribution of the vegetal cover in modifying the rate of delivery, the delivery-pattern, or the impact-characteristics of water reaching the ground-surface. These factors need evaluation since they apparently exert strong influences on soil-dispersion, infiltration, runoff, and the soil-erosion processes.

Surface-storage--Land-use practices that increase temporary surface-storage of rainfall reduce the amount of water subject to direct surface-runoff. Ground-surface storage may be increase by such operations as changes in cropping systems and tillage-practices and the use of plant-mulches and other surface-residues. Water thus stored usually infilters or evaporates.

Any land-use practice that maintains a water-blanket on the soil-surface during rainfall, either by storage or detention, also functions in absorbing the impact of water delivered to the soil-surface. Close-growing vegetation, plant-mulches, and other surface-residues perform this function effectively.

It is recognized that excessive erosional damage may result if large concentrations of water are suddenly released from depression-storage in the absence of adequately designed interception-structures, such as terraces and outlets.

Infiltration--Increasing infiltration is a most desirable objective of water-conservation and soil-erosion control. Information pertaining to infiltration [33] is so extensive as to prohibit comprehensive use of references. Infiltration is the process by which water enters the soil-mass through the immediate soil-surface. Horton [6] suggested infiltration-capacity as the term to use for describing the rate at which water can enter a soil; he also presented a concept of maximum and minimum infiltration-capacities.

There is much evidence that both rate and amount of infiltration on most soils may be caused to vary within wide limits by changes in land-use, cropping systems, and cultural practices, many of which have not been evaluated accurately to date. Obviously, it is impossible to assign characteristic maximum infiltration-capacity values to any soil; the value tends to be a function of surface-treatment rather than of soil-type (Fig. 2). However, as the moisture-content of the soil-profile approaches saturation, land-use conditions become of lesser influence in controlling infiltration-rates. Since minimum infiltration-rate approaches the minimum transmission-capacity of the soil-profile, presumably approximate minimum infiltration-capacity values can be obtained for various soils.

Assuming high initial rainfall-rates, maximum infiltration-rates usually occur at or near the beginning of rainfall. Rates decrease with time of rain, rapidly at first, if the surface-soil structure is either unstable or unprotected, and gradually approach a minimum which is equal to the transmission-capacity of the soil-profile, provided lateral movement does not occur. The status and stability of the soil-architecture (structure in its broadest sense) are the all-important soil-characteristics determining intake, retention, and movement of water in the soil-mass.

Of the several methods that may be used for measuring or calculating infiltration-values, three techniques may be deserving of further development. Infiltration-capacities obtained from hydrograph-analysis probably are frequently low, but nevertheless may be satisfactory for downstream engineering problems. The values obtained are simply approximate estimated averages for the runoff-area considered. The validity of the average rate obtained at any moment is dependent upon the ability of the analyst to estimate the value of such dynamic processes as interception-storage and delivery, detention-storage, and seepage, particularly on mixed-cover watersheds.

The outstanding disadvantage of most infiltrometers, the rainfall-simulators included, is failure to control lateral flow in the soil-mass (tube techniques ignore the dispersive action of both rainfall and runoff as well as the role of entrapped air). Rainfall-simulators probably yield the most usable relative infiltration-rates for evaluating the comparative influences of specific land-use and conservation-practices.

It is believed that marked advancement in the knowledge of infiltration may be made when the continuous changes in soil-moisture are measured directly. Possibly such devices as the Shaw-Baver moisture-meter [34], the Bouyoucos plaster-of-paris block [35], or Fletcher's dielectric method [36], will prove useful in studying infiltration as well as the several processes of soil-moisture depletion.

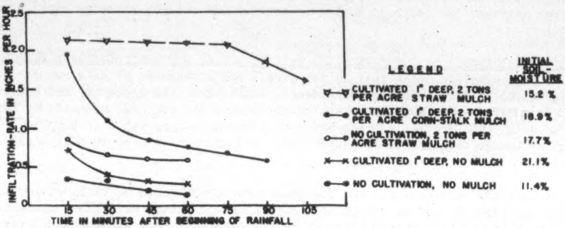

Fig. 2--Effect of mulches and surface-cultivation on infiltration-rates of Muskingdum silt loam (unpublished data of Borst and Woodburn, Soil Conservation Experiment Station, Zanesville, Ohio

Significant correlations have been found to exist between infiltration-rates and non-capillary porosity, organic-matter content, aggregation, total porosity, volume-weight, silt-and-clay content, suspension-percentage, and dispersion-ratio of soils [37].

Temperature influences both evapo-transpiration and percolation-processes, the principal causes of soil-moisture depletion. Hence, temperature is an important factor in determining infiltration dynamics. Theoretically, the temperature-effect of changing the viscosity of water is sufficient, within the normal range of temperature-variation, to cause a twofold change in the rate of movement of water through a fine porous medium. This direct temperature-influence probably takes effect as infiltration-rates approach minimum values.

Some infiltration may occur even when the soil is frozen provided that the non-capillary porosity of the soil is not filled with ice. Both freezing and thawing of the soil should be considered; the exact mechanics involved and the resulting influences on infiltration are not fully understood.

Of special interest are the results being obtained by Duley and others through the use of mulches and residues on the soil-surface [38,39]. Unpublished results of Borst and Woodburn [40], of the Soil Conservation Service Experiment Station, Zanesville, Ohio, are presented in Figure 2. These results were obtained on the same plot within a period of a few weeks--plot-size was 6 by 36 feet; rainfall was applied uniformly at a rate of 2.2 inches per hour in all tests. These data are presented to indicate that further research should be conducted on ways and means of increasing infiltration and controlling erosion by preventing the deterioration of soil-structure at the immediate soil-surface.

In summary, rapid water-movement in the soil is confined almost exclusively to the non-capillary pore-spaces (air-spaces); retention is limited to particle-surfaces and capillary voids between particles or within the interstices of aggregated particles. Any factor that affects the size, shape, continuity, or stability of the non-capillary porosity of a soil may influence the rate and amount of infiltration. Further research is needed on the mechanisms involved in the dynamics of soil-structure formation, deterioration, and regeneration.

Reduction of surface-flow velocities and concentrations--On subareas, defined by the drainage-pattern, the concentration and velocity of flow are determined by the amount of water, physiographic factors, and surface-conditions. One of the functions of vegetal cover, contour-cultivation, and other obstructions to surface-flow is to increase the resistances and reduce the effects of overall slopes so that excessive velocities and concentrations of flow have less opportunity to develop. Vegetal cover may act to increase the resistance by subdividing the flow, increasing the wetted perimeter, and forming residue-dams. Adequate protection must be provided to counteract the tendency of flow to concentrate and attain velocities that develop rills. Field-observations indicate that the type, amount, and distribution of the vegetal cover are important factors in controlling the flow.

With velocity constant, increases in depth through surface-detention increases the distance from the ground-surface to turbulence. Land-use changes that promote the development of a laminar boundary-layer or increase the depth of surface-detention and control velocity merit special attention.

Removal of excess runoff by water-disposal systems--Under any condition or combination of conditions of physiography and soils that do not permit the attainment of safe runoff disposal by means of vegetation or soil- and crop-management, it becomes both necessary and desirable to remove the excess runoff by means of interception-structures and disposal-channels of controlled hydraulic characteristics. Terrace-systems are most frequently used for this purpose. The pioneer efforts of Ramser [41] and Henry and Nichols [42] are outstanding in this phase of erosion-control.

Terraces and similar interception- and disposal-structures should be designed to intercept runoff and delay and lead the excess runoff into safe channels before sufficient concentration and velocity develop to cause excessive rill- or gully-formation; such structures in effect break the slope-length. Velocity is reduced, erosion retarded, suspended load decreased, and more soil left on the field, if the system is properly designed.

Runoff is conducted laterally across the slope, preferably to natural draws or channel-outlets where the water can be handled easiest without causing erosion; excessive volume-concentration should be avoided in so far as is practicable. The entire water-disposal system should be designed and the meadow-strips, sodded waterways, and outlet-ditches stabilized before the interception-structures are actually built.

Drainage-type terraces generally do not materially reduce runoff except on the more pervious soil-types. However, marked changes in rates and timing, and hence erosivity, may be obtained.

Terracing, like other soil- and water-conservation practices, may exert considerable influence on the time-table of hydrologic processes without changing the total amount of water-losses from the land. This principle must be given consideration in relation to the objective sought when attempting to evaluate the influence of specific land-use practices on modifying hydrologic processes.

Increasing soil-resistance to movement by water--Vegetation, plant-residues, and organic matter in the soil and associated micro-biotic activity are the principal natural agents that can be utilized in conservation in increasing the resistance of soil to movement by the dispersive and erosive forces of moving water.

The approximate quantities of root-residue produced by common crops are presented in Table 1. It may be observed from this Table that field-crops fall into two categories:

(a) Soil-depleting crops, such as clean-cultivated row-crops and small grains that require seedbed preparation and cultivation; feeble root-producers and depleting users of soil organic matter; the so-called erosion-promoting crops

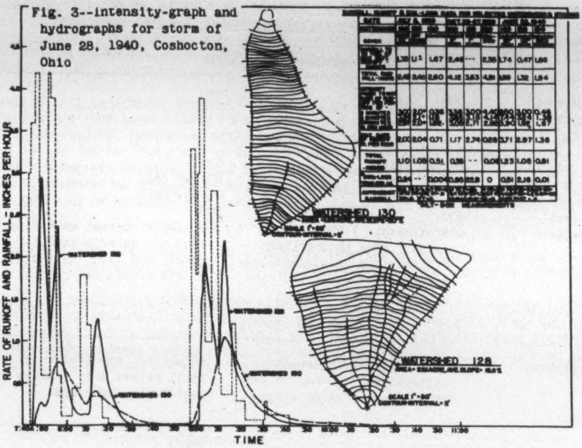

Fig. 3--Intensity-graph and hydrographs for storm of June 28, 1940, Coshocton, Ohio

Table 1--The approximate dry weights of root-residues of field-crops

Crop	Root-residues[1]	Crop	Root-residmes[2]
	Pounds per acre		Pounds per acre
Soybeans	550	Potatoes	321
New alfalfa-sod	3,040	Wheat	767
Old alfalfa-sod	3,900	Corn	1,160
Blue-grass sod	4,900	Alfalfa-sod	3,497
Timothy-sod	5,600	Blue-grass sod	4,500
		Broome-grass sod	3,926

[1] Data from Ohio Agricultural Experiment Station.

[2] Data from Nebraska University Conservation Department, Bull. 12, 1936.

(b) Soil-building crops, such as close-growing legumes, grasses, or legume-grass mixtures that require little or no seed-bed preparation and little cultivation; extensive root-producers and builders of organic matter; the so-called soil-conserving crops

Soil-productivity, or the capacity of a soil to produce vegetation, has long been associated with soil organic-matter content.

Soil-organic matter in colloidal form serves as a binding agent that stabilizes both the soil-aggregates and entire soil-structure against the dispersive and erosive forces of water. Except in the case of the single-grained or "structureless" soils, aggregate rather than textural separates are the particles primarily involved in the erosion-process [16].

Bennett [43] states that "almost without exception soils of low organic-matter content are subject to comparatively rapid erosion."

The direct binding effects of plant-roots have been investigated by Weaver and Harmon [44]. The soil-binding action of roots may prove to be one of the most important factors in increasing soil-resistance to erosion. In 1939, soil-losses from control-plots at Zanesville, Ohio, [12] were 31 tons per acre where corn immediately followed sod, 106 tons where corn was two years removed from sod, and 132 tons per acre where corn was grown continuously. It is apparent that resistance to erosion was largely lost after the grass-roots had decayed.

Table 2--Physiographic description, land-use history, description of precipitation disposal-conditions, and description of surface-runoff for two watersheds

	Physiographic description	
Watershed number	128	130
Area in acres	2.21	1.63
Per cent area by slope-range		
6-10 per cent	24 per cent	None
10-20 per cent	59 per cent	27 per cent
over 20 per cent	17 per cent	73 per cent
Length in feet	400	550
Drainage pattern	Approximately 1,850 feet of channel plus an intricate rill-pattern that completely dissects the watershed into numerous small subareas	One single channel extending uphill from the experimental flume approximately 150 feet, no visible rills or micro-channels present
	Land-use history	
Previous cropping-history	An old field; very low fertility-level; excessive use of clean-cultivated crops	A relatively new field; fertility-level rather low; limited use of soil-depleting crops
Crops by years		
1938	Corn	Run-down meadow; native grasses and weeds
1939	Soybeans	Run-down meadow; native grasses and weeds
1940	Wheat (new meadow-seeding)	New legume-grass seeding, plant-mulch, manure top-dressing
1941	Prevailing clover-timothy hay	Improved alfalfa-clover-timothy hay
	Estimated relative description of precipitation disposal-conditions[a]	
Rainfall-impact	Partially controlled by mature wheat-plants and new meadow-seeding; 100 pounds litter per acre; 100 plants per square meter	Completely controlled by dense new seeding and moderate surface-mulch of trash and residue; 1200 pounds litter per acre; 790 plants per square meter
Interception-storage	Moderate	Moderately high
Interception-delivery	Fair to poor	Excellent
Surface-storage	Low	Very high (plant-mulch)
Infiltration	Rates low with low infiltration-opportunity	Rates medium to low with increased infiltration-opportunity time
	Estimated relative description of surface-runoff[a]	
Depth of surface-detention	Very low	Very high
Characteristics of surface-runoff	Shallow, turbulent surface-flow on small subareas; high-velocity turbulent flow in complex network of rills and deep, narrow drainage-channels	Deep, subdivided, surface-flow was maintained over practically the entire watershed

[a] Based on field-observations during the storm of June 28, 1940, and on its hydrograph-implications.

In recent studies on microbial activities in relation to soil-structure, Peele [45] found that mucous produced by bacteria was an effective binding agent in the formation of water-stable soil-granules; a fungous culture was more effective than a bacterial culture in producing water-stable granulation.

The role of micro-biotic activity in soil-structure changes and resistance to erosion has not been fully evaluated. Field-observations indicate that certain micro-organisms, particularly filamentous fungi, actually bind and tie soil-particles together. Some of the beneficial effects of surface-mulching may arise from a stimulation of microbiotic activity at or near the soil-surface.

Control of soil- and water-movements on natural watersheds--Limited data on soil- and water-movements resulting from three storms on three small watersheds on the North Appalachian Experimental Watershed Project, Coshocton, Ohio, are presented in Figure 3. Runoff-hydrographs for watersheds 128 and 130 for the storm of June 28, 1940, and contour- and drainage-sketches of these two watersheds are included. Only one rainfall-intensity graph (an approximated average for the two watersheds) is included to avoid confusion; such treatment is conservative. Actual rainfall-intensities on watershed 130 were slightly greater and occurred somewhat before those on watershed 128.

Physiography, land-use history, and a relative description of the precipitation-disposal conditions and surface-runoff on June 28 for the two watersheds are described in Table 2.

Figure 3 and Table 2 are presented to illustrate the paper and show how the forces and processes of erosion arising from surface-water movements on natural watersheds may be counterbalanced by combinations of land-use practices to obtain erosion-control under field-conditions. The force-resistance concept presented has been extremely helpful to the authors in planning and conducting research in soil- and water-conservation.

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DISCUSSION

G. W. MUSGRAVE (Soil Conservation Service, Washington, D. C.)--The fall of a drop of water: One of the factors which determines the rate of infiltration of water into soil and consequently the rate of erosion is the energy of impact of the falling drop upon the land's surface. This has been referred to in Dr. Yoder's paper. In a paper which was presented at the Section of Hydrology, the velocity of fall of drops of different sizes was reported by Laws. On the basis of measurements made in a very ingenious set of experiments, it was found that a drop three mm in diameter has a terminal velocity of between seven and eight meters per second. During the course of a natural rain, drops which are both larger and smaller are probably common but it is apparent in any event that the total amount of applied energy by a large number of drops which are falling with this velocity may be very great indeed--even exceeding the energy developed by the rapidly moving water on the land's surface.

When turbidity of surface-water results from any cause there is a very great reduction in infiltration so that runoff (and erosion) is greatly increased. Lowdermilk as early as 1926 showed the pronounced effect of turbid water in reducing the rate of infiltration. A study of a falling drop and its effect upon different soils, when dry, or wet, or flooded, is important to any consideration of protective effects and procedures which may be developed.

The stroboscopic photographs of Professor Edgerton at Massachusetts Institute of Technology showing the fall of a drop of milk (the beauty of these photographs is such that they have been widely reproduced in popular journals and newspapers) led to the development of plans by the Chief of the Soil Conservation Service for the preparation of photographs of a falling drop of water upon soil. These photographs were recorded upon moving picture film and since they nicely represent one phase of the dynamics of the erosion-process, it is pertinent to the present discussion. A part of the film--merely a sufficient portion to indicate one or two very interesting points--was shown.

The sizes of drops used for the motion picture (1/4-inch diameter) comes within the range of sizes studied by Laws and included in the paper referred to. A scale in the margin of the pictures indicates the actual dimensions. Without some explanation one might suspect that the fall of this drop upon dry kaolin was not the fall of a drop of water, but the fall of a high-powered bomb. Of course, the size of the crater, the distance to which the particles move, as well as their velocity, varies with different soils and their chemical and physical properties. On wet soils, the explosive effect is not as pronounced, the moisture in the soil itself having served to cement the individual particles somewhat.

On flooded soils the effects perhaps may be divided into four parts: (1) The drop strikes the flooded surface; (2) a crater is formed, the "collar" of which is not unlike in appearance a section of the widely circulated photographs by Edgerton of a drop of milk; (3) a later stage shows the recession of the collar with a filling of the crater and the beginning of the very interesting formation of a miniature geyser--the fourth step.

The photographs show the geyser to be dark in color and that it undoubtedly is loaded with soil. Clearly, the drop falling upon a flooded surface has sufficient energy to develop considerable turbidity of surface-water.

This is neither the time nor the place to follow completely the consequences of the effect of this falling drop. We can readily see that certain forces are in operation and that they comprise a portion of the problem of the dynamics of erosion. Yoder has shown how studies made and under way are bringing to light the forces of resistance to erosion as found in soils of different chemical and physical properties and also how various protective procedures may be interposed against them. Both the complexities of the erosion-problem and its importance to the Nation's welfare demand the best efforts of the research worker engaged in its investigation.

WALDO E. SMITH (Soil Conservation Service, Washington, D. C.)--There is one small item that I would like to mention before this mixed group composed largely of soils people and engineers. Hydrology is a borderline field in which hydraulic engineers, agronomists, meteorologists, and others have interest, and certain terminology has come to be common. Unfortunately, this is not true in all cases. One item of terminology that falls in the second category and that appears in the draft of this paper is the term "losses," relating to disposition of rainfall. To the hydraulic engineer the term "losses" means water that soaks in and is not available at a point downstream to augment the total flow. To soils people the term means the water that goes downstream, that is, it is lost as far as its availability to plants at the point at which it falls is concerned. I think, to avoid confusion, it would be well for those who work in hydrology to eliminate the use of this term, inasmuch as the two uses mean opposite things.

ROBERT E. HORTON (Voorheesville, New York)—Sheet-erosion--present and past

Sheet- versus channel-erosion--The soil-erosion reconnaissance maps of the United States Soil Conservation Service show soil-erosion to be taking place in a greater or less degree over a large portion of the United States. Even more significant to the present discussion is the fact that these maps also show extensive areas on which there is no evidence of appreciable erosion at the present time. These regions include sandy coastal plains, as in southern New Jersey, some loess-covered regions in the Mississippi Valley, such as that between the Yazoo and Mississippi rivers in western Mississippi, desert regions, and glaciated regions with permeable soils, such for example as the greater portion of the State of Michigan.

Books on physiography do not always distinguish clearly between sheet- and channel-erosion, and erosion-effects commonly credited to channel-erosion are quite certainly often the result of sheet-erosion. Sheet-erosion has undoubtedly taken place on many areas in varying degrees of intensity throughout long eras of geologic time--as long, in fact, as there has been rain and soil, and during all this time sheet-erosion has been due to the same physical processes by which it is now governed. Much has been learned about these physical processes in recent years, and while there is yet much to be learned, it seems worth while briefly to take stock of the situation and, in particular, to inquire as to the extent to which presently observed conditions and erosion-rates can be reconciled with the historic record revealed by existing landforms.

Two principles or assumptions will be made to start with:

(1) That in humid regions existing drainage-basins of streams have been carved out of the landscape by aqueous erosion.
(2) That this has been for the most part sheet-erosion--not channel-erosion.

With reference to the second assumption, it may be noted that the fraction of the carving and the gradation of drainage-basins which has resulted from channel-erosion is apparently about the same as the ratio of the total stream-area within the drainage-basin to the total surface-area of the basin. This, even in well-drained basins, is of the order of one per cent, and in regions of low drainage-density, much less. In other words, it appears certain that throughout the period covered by the gradation of drainage-basins from their inception to their present forms, something like 99 per cent of the soil-removal has taken place initially as a result of sheet-erosion.

One reason why so much more attention has been given to channel-erosion than to sheet-erosion is that it is much more conspicuous. Large volumes of sediment are seen and measured in streams during floods. It should not be forgotten that floods originate on the ground-surface--not in the stream-channels where they are observed. A sheet of water 1/4 inch deep, flowing over the ground-surface with a velocity of one foot per second, will produce a surface-runoff of 110 cubic feet per second per mile of stream-frontage, or 22,000 cubic feet per second from a drainage-basin of 100 square miles, with drainage-density unity and a total stream-length of 100 miles. This would be a major flood in the stream-channel, yet the overland or sheet-flow which produced it would hardly be noticed by a person walking over the ground during the rain.

If this sheet-flow was able to carry and did carry ten per cent by volume of suspended soil-matter, and lasted six hours, it would remove 1/5 inch depth of solid soil-material or 1/4 to 1/3 inch depth of actual soil. It is in this inconspicuous way that

Little drops of water
Little grains of sand,
Run away together
And destroy the pleasant land.

Marginal belt of no erosion--Much effort is now being directed to the reduction of soil-erosion through artificial measures, such as improved crop rotation and tillage-practice, strip-cropping, forestation, restoration of grassland, and terracing where practicable. It is not, however, as generally recognized as it should be that such measures are of two kinds: (1) Those which reduce but do not inhibit sheet-erosion on the treated areas; (2) those which prevent or inhibit sheet-erosion.

Reading current books on physiography, agriculture, and engineering, one may easily gain the impression, tacitly if not by direct statement, that (1) rain always produces runoff, (2) that runoff always produces some degree of erosion. Neither of these propositions is true. If they were both true, little could be accomplished in erosion-reduction and nothing whatever in its inhibition.

Not until the writer developed the concept of infiltration-capacity [see 1 of "References" at end of paper] and applied it in the development of the infiltration-theory of surface-runoff [2] did the true relation between rainfall and surface-runoff emerge. At about the same time

Middleton and his associates [3] developed the idea of initial resistivity of the soil to erosion. As a result of these two factors, it now appears that:

(1) Surface-runoff does not occur in a given storm unless the rain-intensity exceeds the coincident infiltration-capacity of the soil. If this condition exists, then the runoff-intensity approaches a value equal to the difference between infiltration-capacity and rain-intensity as a limit.

(2) Sheet-erosion does not occur unless the runoff-intensity produces a tractive or erosive force acting on the soil-surface greater than the initial resistivity R_1 of the soil to erosion.

Middleton's erosion-index is intended to give the initial relative resistances of different soils to the erosive action of overland flow, using the term "soil" with the meaning of more or less comminuted mineral matter, which may contain also organic matter in the form of humus. Actually, as regards sheet-erosion, soil-characteristics alone do not suffice to determine initial resistance. Not only the soil per se but also the slope, micro-topography of the surface, the density and character of different zones of vegetal cover, if any, and the macro-structures in the soil, including grass and other plant-roots as well as other biologic structures, are involved in determining both the initial resistance of a given region to sheet-erosion and the rate at which such erosion takes place after the initial resistance is overcome. It seems, therefore, more appropriate to speak of the resistance to erosion of a given terrain rather than that of a given soil.

One of the direct results which follows from recent advances in relation to surface-runoff and soil-erosion is that, however active sheet-erosion may be farther down the slope, there is always a marginal belt adjoining the crest or watershed-line on any slope, within which sheet-erosion never occurs. The width of this belt may vary from a few inches or a few feet in aggravated cases of active erosion, to a width of hundreds of yards or even a mile or more in cases where the initial resistivity of the terrain to sheet-erosion is high relative to the runoff-intensity. The width of this belt of no erosion is determined primarily by two factors, other things equal: (1) The infiltration-capacity of the soil; (2) the initial resistivity of the terrain to sheet-erosion. It happens that these two factors are more or less subject to artificial control and it is because of this fact that measures can often be applied which will be effective not only in reducing sheet-erosion but in completely preventing it. If, for example, on a given slope the width of this belt of no erosion is, under certain conditions, small relative to the length of slope from the watershed-line to a stream, then erosion will occur over the greater portion of the slope. If, now, through artificial means, the width of this belt of no erosion can be increased to a value greater than the total length of overland flow, then sheet-erosion will be inhibited on the entire slope.

Examples are needed to show the importance of the critical distance x_c, or width of the belt of no erosion, in relation to erosion-control. The width of the marginal belt of no erosion is, as already stated, controlled chiefly, other things equal, by infiltration-capacity and initial resistivity of the soil, and in a given storm this belt extends to a distance from the watershed-line such that the erosive force of sheet flow becomes equal to the initial resistivity.

Let i = rain-intensity, inches per hour; f = infiltration-capacity, inches per hour; q_c = runoff-intensity per foot of slope, in cubic feet per second, necessary to provide an erosive force equal to the initial resistivity R_1. Then except for very short storms the runoff-intensity will become approximately $(i - f)$, in inches per hour, and the value of q_c will increase uniformly with the distance x from the watershed-line. Then since one inch of runoff per hour is approximately equal to one second-foot per acre, or precisely one second-foot for 43,200 square feet

$$q_c = (i - f)x/43{,}200 \tag{1}$$

and

$$x_c = 43{,}200\, q_c/(i - f) \tag{2}$$

If, for example, $i = 1.0$, $f = 0.25$, and $q_c = 0.005$, then equation (2) gives $x_c = 288$ feet. Suppose f is doubled or increased to 0.5 inch per hour, then $x_c = 432$ feet, or the width of the belt of no erosion is increased 144 feet or 50 per cent. Usually the increase of infiltration-capacity f does not take place alone but, especially if good vegetal cover is substituted for poor cover, it is accompanied by an increase of R_1 and q_c. Suppose R_1 is quadrupled, as may easily follow from good grass or forest-cover replacing bare soil or poor cover, this will not quadruple q_c. The experimental data available indicate that the erosive force of sheet-flow varies about as the square of the runoff-intensity q, in which case q_c would be at least doubled if R_1 is quadrupled, giving for $i = 1.0$ and $f = 0.50$, $x_c = 864$ feet. Hence, as the result of increase of f from 0.25 to 0.50 inch per hour, with an increased R_1, by substituting good for poor cover, the width of the belt of no erosion is increased from 288 feet to 864 feet.

If it happens that the value of x_c in all storms after treatment exceeds the actual length of overland flow from the watershed-line to the stream, then sheet-erosion will be inhibited or completely controlled on the given slope.

These examples serve to show that important accomplishment in the way of complete control of sheet-erosion is not difficult in case (1) the natural terrain is amenable to treatment by practicable methods, (2) rational methods based on sound hydrophysical principles are used. Much more startling examples can easily be given. In a region where drainage-development is stable, the average length of overland flow measures approximately the width of the belt of no erosion. In the region around Copper Hill, Tennessee, the average length of overland flow to streams was of the order of 1/4 to 1/3 mile before the natural vegetal cover was destroyed by smelter fumes. The destruction of most of the vegetal cover had the effect of decreasing the initial resistance to sheet-erosion and with it the critical distance x_c, or the width of the marginal belt of no erosion, to a matter of a few yards or rods. Upland dissection by active erosion ensued until Nature restored a balance between erosive force and initial resistance by increasing the drainage-density tenfold or more, ruthlessly destroying the upland in the process.

Drainage-basin development by sheet-erosion--Confusion has arisen in some cases in the discussion of the relationship of sheet-erosion to the controlling independent variables through failure to distinguish between erosion-rate and transporting capacity. In a given storm on a given slope the sheet or overland flow may be charged to transporting capacity with suspended material. In that case the rate of surface-soil removal is governed by the transporting power of overland flow.

Both eroding power and transporting power are unquestionably functions of depth and velocity of overland flow, and since runoff-intensity at a given point on the slope is proportional to the product of depth and velocity of overland flow, either the eroding power or the transporting power can be expressed approximately as a function of runoff-intensity. This is only an approximation, for the reason that a depth of overland flow of one inch, with a velocity of 1/2 foot per second, on one slope, gives the same runoff-intensity as a depth of sheet-flow of 1/2 inch with a velocity of overland flow of one foot per second. The eroding power of the sheet-flow may not be the same in the two cases; neither may the transporting power be the same.

At the present time we do not know the functional relationship between depth and velocity of overland flow and either the eroding power, or the transporting power. Meager experimental data presently available, however, indicate that within a certain range, either eroding power or transporting power can be expressed in a purely empirical way, with approximate accuracy, as a simple power or parabolic function of runoff-intensity. The term "parabolic function" is used in this paper in the sense of a function of the form $y = kx^m$, the common parabola being a particular case where $m = 1/2$.

Much attention has been given to the subject of the forms of stream-profiles produced by channel-erosion. So far nothing has been published, so far as the writer is aware, relative to the form of valley-profiles or cross-sections produced by sheet-erosion.

Referring to Figure 2, for uniform conditions the runoff-intensity in a given storm is proportional to the distance x from the watershed-line. Close to the watershed-line there will be a belt of width x_c on which no erosion occurs. Assuming for the present discussion that this belt is of negligible width compared with the total slope-length L, the runoff-intensity will be proportional to the distance x. If the sheet-flow is charged with suspended matter to its full transporting capacity, then the quantity of suspended matter carried past any point x will be proportional to a power-function of x, or $e = x^m$. This will represent the total or integrated rate of erosion from the watershed-line to the point x, or in the form of an equation

$$kx^m = \int_0^x e\,dx \tag{1}$$

where e is the rate of erosion at the point x. Differentiating, this equation gives

$$e = mkx^{m-1} \tag{2}$$

Experimental data show that m is greater than unity. Consequently equation (2) is that of a parabolic curve with exponent (m-1). The total depth of erosion or soil-removal at a given point

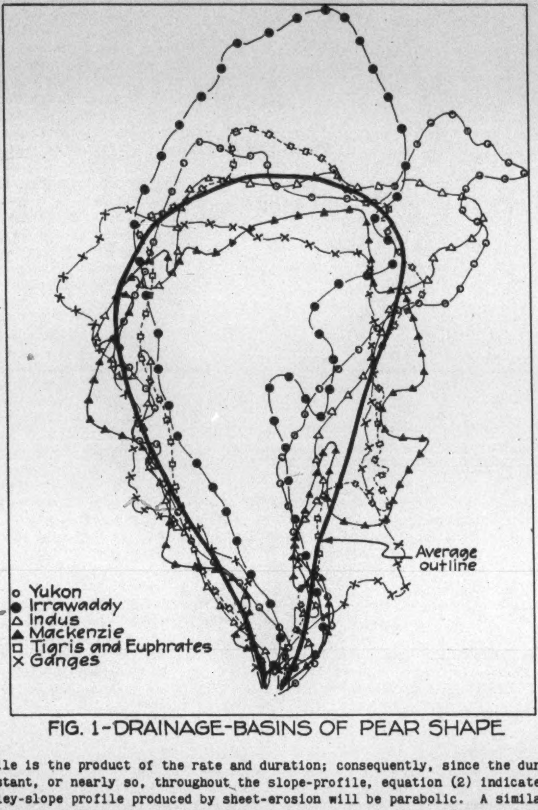

FIG. 1-DRAINAGE-BASINS OF PEAR SHAPE

on the profile is the product of the rate and duration; consequently, since the duration is usually constant, or nearly so, throughout the slope-profile, equation (2) indicates that the form of valley-slope profile produced by sheet-erosion will be parabolic. A similar result follows if it is assumed that the sheet-flow is not fully charged with sediment but the rate of erosion is a parabolic function of runoff-intensity. The result is approximate and will be modified to some extent in cases where, as is usually true, the belt of no erosion adjacent to the watershed-line has an appreciable width relative to the slope-length and by other causes. This simple, incomplete analysis suffices to provide a rational basis for a fact, quantitatively determined in many cases where reservoirs have been constructed in stream-valleys and the approximate volume of the valley determined. As a rule, the volume-depth curve has a form which shows that the valley cross-sections and profiles are approximately parabolic, though not necessarily common parabolas. Hundreds of such reservoir volume-depth relation curves have been derived, so that this may be taken as an established fact. The analysis indicates that this result follows if the valleys have been developed chiefly by sheet-erosion; in other words, this is a competent cause of observed valley-forms.

Further proof that the valley-forms of drainage-basins have resulted mainly from sheet-erosion processes is obtained by comparing the actual forms of the outlines of drainage-basins with the form which would be produced in accordance with equation (2) above given. For the purpose of this comparison the outlines of drainage-basins of a number of the larger rivers of the world were drawn on such a scale that they enclose equal areas and were superposed with their outlets coincident, as shown on Figure 1. The individual outlines are all roughly pear-shaped ovoids and the major differences, as in the case of the Irrawaddy River, are due to differences in the width-length ratios for the different drainage-basins. The heavy line on Figure 1 shows the average form of the outlines of these drainage-basins.

Now assuming that a drainage-basin has been developed by gradation of an initially inclined, uniform plane, ab, Figure 2, in accordance with equation (2), producing the valley-profile acb, roughly parabolic in form, and that the cross-sections of this valley-profile are also parabolas, the plan or outline of the watershed which would result under these conditions is easily determined and is as shown on Figure 2. This is a pear-shaped ovoid closely resembling in form the boundaries of actual drainage-basins shown on Figure 1.

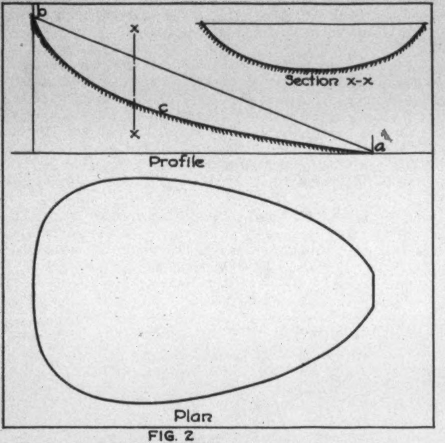

FIG. 2
PEAR-SHAPED WATERSHED-LINE OF A DRAINAGE-BASIN PRODUCED BY SHEET-EROSION ON AN INCLINED SURFACE

Terracing--The reason commonly given for the efficacy of terracing in reducing sheet-erosion on a terraced slope is that, if a slope with a total area A is divided into n sub-areas, the runoff-intensity from each sub-area will be reduced in proportion to the ratio of the sub-area to the total area. The infiltration-theory of surface-runoff shows that the reduction in runoff-intensity (in cubic feet per second) is not as great as the reduction in area or slope-length on a terraced slope, and this result is well confirmed experimentally. While the explanation above given accounts for a large reduction of erosion by terracing, it does not account for the elimination or complete control of sheet-erosion between terraces. Yet it is well known that adequate terracing of an eroding slope will completely control sheet-erosion.

The correct explanation lies in the fact that adequate terracing reduces the length of overland flow to a value less than the critical distance x_c from the watershed-line required to permit erosion to take place. In other words, if, after terracing, the minimum distance x_c from the watershed-line required to overcome initial resistance to erosion in the maximum storm is greater than the slope-length ℓ between terraces, no sheet-erosion can ever occur between the terraces.

Regions of no erosion--Returning now to the soil-erosion maps, portions of the State of Michigan on which the map shows no active erosion will be used for illustration. Much of the area is now under cultivation but this region was heavily timber-covered less than a century ago, a condition which certainly would be still less productive of sheet-erosion than cultivation. The region is covered with a heavy veneer of glacial origin, including ground-moraines, terminal moraines, and outwash plains, pock-marked with glacial kettle-holes. Material left behind by a retreating ice-sheet is already more or less comminuted and in an advanced state of productive soil-formation. As a rule, it contains all requisite minerals, since it is composed of a mixture of rock material derived from different sources. When such material is newly exposed under suitable climatic conditions, if not too coarse-textured, vegetation quickly develops. At the present time the runoff is mostly ground-water flow--in fact, something like 40 per cent of the Kalamazoo River Drainage-Basin, for example, is tributary to glacial kettle-holes and shallow depressions which never overflow and hence provide no direct surface-runoff to the streams. Observations in areas containing primeval forest show that where the soil is moderately sandy, no surface-runoff ever occurs at the present time. On the remainder of the area direct surface-runoff does occur after winter and spring thaws, when the soil is still frozen and its infiltration-capacity reduced to a minimum, but direct surface-runoff rarely if ever occurs on much of this area under summer conditions because of the high infiltration-capacity of the soil. In spite of these conditions, streams and their drainage-basins are fairly well developed. Streams such as the Kalamazoo, Grand, St. Joseph, and Huron rivers have main channels incised 100 feet or more below the adjacent uplands. Tributary streams are extremely youthful, in the geologic sense. Detailed observation of the countryside indicates that much of the topography outside the stream-valleys is today almost precisely as it was when the ice disappeared.

The entire picture suggests strongly that the topographic development of drainage-basins and their stream-systems as now observed took place very shortly after the glacial ice disappeared, and under somewhat different climatic and cover-conditions. This could easily have occurred with a greater degree of soil-frost, with consequent low infiltration-capacity and easily erodible, unprotected soil-surfaces. The vegetal cover developed at an early stage and increased the resistivity of the soil to erosion and, with it, increased the width of the marginal belt of no erosion to a point where it equalled the actual length of overland flow. Drainage-basin development by sheet-erosion was then arrested and has remained in status quo to the present time.

Where a loessal veneer occurs, it bears evidence that sheet-erosion was already inhibited or else could not keep pace with the aeolian deposits, and here, as elsewhere where no erosion occurs over extensive areas, it is certain that Nature has provided by one means or another, and apparently chiefly by grass-cover or forestation and high permeability of the soil, natural measures completely preventive of sheet-erosion in this region on a relatively large scale. The same thing can be done by human agencies by following Nature's methods.

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DYNAMICS OF ENTRAINMENT OF EROSIONAL DEBRIS AND SEDIMENTATION

Carl B. Brown

Study of the problem of modern sedimentation is, in essence, an analysis of the corpus delicti--the waste products--of soil-erosion. The objectives of such a study are to locate and appraise the effects of erosional waste, to establish the laws that govern the transportation of sediment from its places of origin to its places of deposition, to determine quantitatively the sources of each type of erosional waste causing each type of sedimentation-damage, and lastly, to develop measures designed to minimize the damages, and, where possible, to create benefits from the stream-borne sediment. A few of the recent findings will perhaps best illustrate the relation of sedimentation to the dynamics of erosion in this new land of ours.

Studies of silting damage to storage reservoirs [see 1,2 of "References" at end of paper] have disclosed that maladjustment of reservoir-size to the physical characteristics of the drainage-area is a principal cause of excessive loss of storage. Using data from reservoirs that trap a major part of the sediment delivered to them, it has been found that the rates of sediment-output from drainage-areas of more than two square miles fall within a relatively narrow range--a range much smaller than that shown in erosion-plot measurements--despite wide variations in erosion and land-use on the watershed.

Figure 1 shows two regions from which data have been analyzed. In the Southeastern Area (Fig. 2) 77 per cent of the surveyed reservoirs that have an original capacity greater than 15 acre-feet per square mile of drainage-area are trapping sediment at rates of between 25 and 125 acre-feet per 100 square miles annually. In the Plains region the range is somewhat wider, but 91 per cent of the reservoirs are trapping sediment at rates between 25 and 250 acre-feet per 100 square miles annually.

The rate of silting of a reservoir depends on three factors, namely, (1) the rate of sediment-delivery by inflowing streams, (2) the percentage of incoming sediment permanently trapped, and (3) the ratio of the original storage-capacity to the rate of sediment-accumulation. The percentage of sediment trapped decreases rapidly as the capacity of the reservoir falls progressively below 15 acre-feet per square mile of drainage-area. Thus, for reservoirs that have a sediment-accumulation of less than 25 acre-feet per 100 square miles an explanation nearly always may be found either in the low ratio of reservoir-capacity to drainage-area, or in a practice

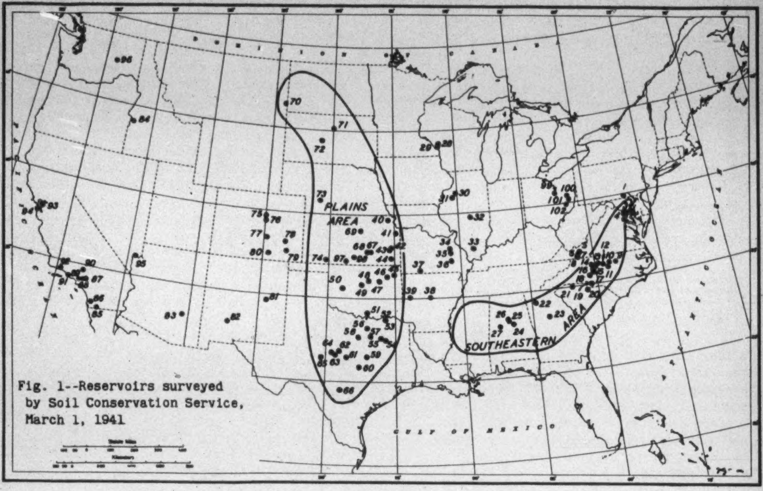

Fig. 1--Reservoirs surveyed by Soil Conservation Service, March 1, 1941

Legend

No.	Reservoir	No.	Reservoir	No.	Reservoir
1	Palington	35	Shepherd Mt. Lake	69	Ottawa Co. State Lake
2	Greenbelt	36	Mountain Lake	70	Baker
3	Burnt Mills	37	Lake Taneycomo	71	Lake Hurley
4	Barcroft	38	Lake Bennett	72	Hayes Lake
5	Buck	39	Lake Booneville	73	Wellfleet
6	Byllesby	40	Mission Lake	74	Meade Co. State Lake
7	Washington Mills	41	Lake Olathe	75	Kenwood
8	Field's Mfg. Co.	42	Kirk Lake	76	Castlewood
9	Franklinton	43	Lake Moran	77	Teller
10	Lake Michie	44	Neosho Co. State Lake	78	Horse Creek
11	University Lake	45	Lake Spavinaw	79	Muddy Creek
12	Burlington	46	Lake Claremore	80	Brown No. 1
13	Greensboro	47	Lake Sapulpa	81	Alamogordo
14	Lake Salem	48	Boomer Lake	82	Elephant Butte
15	High Point	49	Guthrie	83	San Carlos
16	Lexington	50	Clinton	84	Black Canyon
17	High Rock	51	Ardmore Club Lake	85	Morena Lake
18	Lake Concord	52	Crook Lake	86	Hodges Lake
19	Lake Lee	53	Gibbons Lake	87	Live Oak
20	Lancaster	54	Grand Saline	88	Santa Anita
21	Spartanburg	55	Wills Point	89	Devil's Gate
22	White Manganese	56	Lake Dallas	90	Little Rock
23	Lloyd Shoals	57	White Rock	91	Sherwood
24	Lay	58	Texas and Pacific R.R.	92	Lake Gibraltar
25	Lake Purdy	59	Lake Waco	93	Upper San Leandro
26	Bayview	60	Rogers Lake	94	Upper Crystal Springs
27	Harris Lake	61	Lake Merritt	95	Lake Mead
28	Ettrick Lake	62	Lake Brownwood	96	Bennett Desilting Basin
29	Lake Marinuka	63	Santa Anna Lake	97	Medicine Lake
30	Lake Calhoun	64	Lake Scarborough	98	Bennington Lake
31	Lake Bracken	65	Lake Nasworthy	99	Pleasant Hill
32	Lake Decatur	66	Lake Medina	100	Tappan
33	West Frankfort	67	Lake Eldorado	101	Piedmont
34	Grisham Lake	68	Santa Fe	102	Senecaville

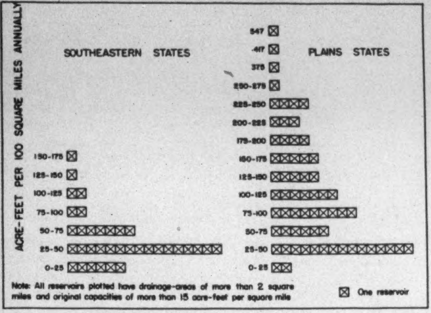

Fig. 2--Sediment-accumulation in surveyed reservoirs

of water-release at the dam that vents much of the sediment, or in the low sediment-output from the drainage-area. Unusually high rates of sediment-accumulation per unit of drainage-area nearly always result from the reverse of these conditions and are associated with conspicuous erosion in the drainage-area. In other words, the probability of rates above or below these prevailing limits can be forecast by a study of watershed-characteristics, if the size and operating practice of the reservoir is known.

As an example, let us consider the Sardis Reservoir, completed for flood-control this year with a capacity of 1,570,000 acre-feet, on the Little Tallahatchie River, Mississippi. Its drainage-area of about 1,453 square miles, exclusive of the reservoir-basin, has suffered an intensity of accelerated soil-erosion that is hardly equaled by any area of comparable size in the United States. Yet, if an annual erosion-rate of 250 acre-feet per hundred square miles--the upper limit of measured rates in the Southeast--were assumed, the capacity-loss would be only 23 per cent in 100 years. In fact, measurements of the suspended-sediment load and of valley-sedimentation within the Sardis Reservoir Basin have led to the estimate that silting will deplete the capacity of this reservoir between 12 and 18 per cent in 100 years, equivalent to 130 to 194 acre-feet of sediment per 100 square miles of drainage-area annually. In this case a comparatively low rate of silting will result despite extreme erosion because a very large ratio of storage to drainage-area was achieved, namely, 1,081 acre-feet per square mile.

On the other hand, let us consider the Osborne Reservoir, built in 1936 for water-supply on the Solomon River at Osborne, Kansas. The original reservoir-capacity was small, only about 300 acre-feet, whereas the drainage-area was large, about 2,100 square miles. Even if the sediment-production from this drainage-area had been assumed to be as low as five acre-feet per hundred square miles annually, it would have been obvious that the reservoir would fill in less than three years and would be useless for storage-purposes. Actually, it was completely silted the first year. In this case a very poor adjustment of reservoir-size to drainage-area was made, as the capacity was only 0.14 acre-foot per square mile.

It is surprising how many engineers have overlooked this problem of adjusting reservoir-size not only to water-needs and runoff but to sediment-load. This principle of the limited range of debris production makes it possible henceforth to take this factor into account in design, and to predict from regional indices of sediment-production developed through widespread reservoir-surveys and sediment-load measurements the order of magnitude of the silting rate and the relative need for sediment-control measures within the limits of design to which a specific reservoir must be restricted.

Let us turn from the problem of reservoir-silting to the effect of sediment in valleys on floods. In many sections of the country it has been found practicable to identify and measure the volume of sediment deposited in stream-valleys within the modern period of accelerated erosion [3]. Distinction between the modern valley-deposits and the older valley-alluvium has been based on a number of criteria, the most important and widely applicable one of which is the recognition by darker color, different texture, structure, and concretionary content of buried old soil-horizons. The validity of this criterion has been demonstrated by tracing the buried soil-horizons into lateral continuity with surface colluvial or upland soils bordering the valleys, and confirmatory evidence has been found in the depth of burial of cultural objects, trees, and fence posts.

Among the several significant findings that have come from these valley-sedimentation studies is the principle that deposition on flood-plains of fine sediment coming chiefly from sheet-erosion may cause an increase in the area of inundation and resulting flood-damage without increase in flood-discharge. This principle has not heretofore been generally recognized in flood-control plans.

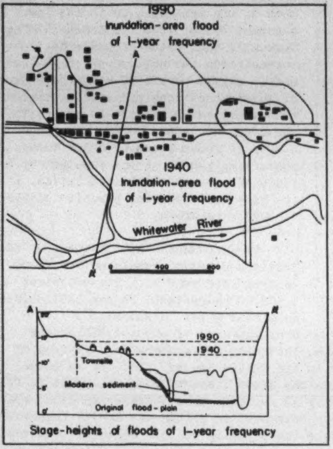
1990
Inundation-area flood of 1-year frequency
A
1940
Inundation-area flood of 1-year frequency
Whitewater River
A'
0
400
800
A
A'
10'
5'
0'
1990
1940
Townsite
Modern sediment
Original flood-plain
Stage-heights of floods of 1-year frequency

Fig. 3--Flood-conditions at Elba, Minnesota

Let us consider the situation at Elba, Minnesota, on the Whitewater River (Fig. 3) where, if the average rate of valley-sedimentation since accelerated erosion began, shown by the accumulation in the cross-section, is allowed to continue in the future, the area inundated by flood-flows of one-year frequency will increase until 50 years hence virtually the whole townsite will be flooded every year. A similar condition may be expected wherever low river terraces border flood-plains on which rapid sedimentation is occurring concurrently with sufficient channel-fill to maintain about the same bank-full capacity for flood-flows.

Solution of many of the problems of valley and channel, as well as reservoir, sedimentation awaits more complete knowledge of the laws of transportation of sediment. Recent research on the transportation of bed-load and suspended load in relation to the discharge-characteristics of a stream is therefore of particular significance. Suspended and bed-load in varying proportions are known to cause different types of sedimentation-damage. River-channel aggradation, for example, is largely caused by bed-load; the cost of filtering public water-supplies may be attributed chiefly to suspended load; while silting of reservoirs is a result of deposition of both bed-load and suspended load.

In planning for sedimentation-control we must determine what effect different measures will have, not in reducing the total load of a stream, but in reducing those component parts of the load that are chiefly responsible for particular types of damage. Until recently any attempt to answer this question was greatly hampered by lack of quantitative data on the rates of movement of bed-load as compared with suspended load.

Beginning January 1, 1939, the Soil Conservation Service put into operation a unique installation on the Enoree River near Greenville, South Carolina, which permits for the first time direct measurement of the total load of a natural stream, including the part that moves along the bottom as well as that part within the range which can be sampled by suspended-load samplers [4]. Records being obtained at this station include discharge, the volume of material moving along the bed as well as the volume of suspended load both analyzed by per cent in 13 grade-sizes, the dissolved load, turbidity, water- and air-temperature, and rainfall at 11 stations in the 64.4-square mile drainage-area.

From the data obtained in 1939, Einstein, Anderson, and Johnson [5] have found that sediment in this stream larger than 0.35 mm moves at a rate related to the stream-discharge, mostly below the zone of suspended-load sampling and that it constitutes most of the material found in the stream-bed at low water. Thus they have defined bed-load as material coarser than a critical grade-size which moves at a rate related to discharge. During 1939, 532 tons of sediment or three per cent of the total load of 17,760 tons passing the Enoree River station was coarser than this critical grade-size. Enough of the coarse material occurs in the stream-bed to saturate the flow in those grade-sizes for any discharge within the range of stage yet observed at the station.

On the other hand, the lack of correlation between suspended-load concentration and discharge indicates that the fine material is merely "washed into" the stream-flow (including, of course, that "washed in" as a result of stream-action on its own banks). For this finer load it appears that the stream would have a capacity many times the amount that would ever be available.

One significant conclusion to be drawn from the Enoree River data is that more than 90 per cent of the total sediment-load passing the control-point on this stream is fine material or "wash load" picked up at some point in the drainage-basin (including stream-banks) and transported from this point of origin to the control-station during the runoff which caused the original entrainment.

If the basic relationship of suspended load, bed-load, and discharge on the Enoree River is confirmed on most other streams, as seems probable, this will constitute a convincing refutal of the often advanced argument that conservation practices can have little effect for many years because of the large quantities of sediment already in transit through the stream-systems. This could be true only where the damage comes chiefly from bed-load, as in channel-aggradation. Where the finer sediment is of major importance, as in the silting of most reservoirs, conservation practices may be expected to have a rapid and enduring effect.

The problem of silt-laden density-currents in reservoirs and the possibility of their utilization to decrease rates of silting has been under intensive investigation in several reservoirs in the field and by several laboratories where experimental underflows of this type have been measured.

Turbulence and its effect on the transportation of sediment in suspension has been intensively studied. Laboratory research at the California Institute of Technology reveals that concentrations of finer sediment in a flow are, in general, larger than should be the case if the theoretical assumption were true that the coefficient for turbulent transfer of suspended sediment is the same as the coefficient for the turbulent transfer of momentum. The difference between observed behavior and theory appears to be greater as the sediment is finer and diminishes as the suspended load becomes coarser. Further experiments may show that material coarser than some critical size will occur in smaller quantities than should be the case according to this turbulence theory. One corollary of this basic finding is that sediment suspended in a flow tends to reduce appreciably the turbulent transfer of momentum and hence resistance to flow, allowing the sediment-laden water to move faster than a comparable clear-water flow. Another conclusion is that suspended load tends to produce instability of flow and may be a factor in causing secondary circulation observed in rivers. The full significance of these findings to river and sediment-control problems is not yet clearly foreseen.

It is clear, however, that the full solution of sedimentation-problems will require a twofold approach involving both (1) the utilization of the laws of sediment-transportation to control sediment-movement in streams as a means of preventing damages and, where possible, creating benefits, and (2) the development of plans for arresting the production of damaging sediment at its source. Control of sediment-production will have the most enduring results. To achieve satisfactory control we must first determine quantitatively the sources of the damaging parts of the total sediment-load, and secondly must establish protective measures on drainage-areas in due proportion to these sources of damaging sediment.

We must not make the false assumptions that any percentage reduction in the total sediment-load of a stream will effect a portionate reduction in sedimentation-damage, nor that prevention of any percentage of the gross erosion on the drainage-area would effect a proportionate reduction in the stream-load.

The differences in amounts of stream-load and of erosion-losses from the land-surface is well illustrated in Figure 4, which is based on data obtained from an unpublished report by Hoyt [6]. Five plots of 2 to 3 1/4 acres under different land-use treatment at the Clarinda, Iowa, Conservation Experiment Station during 25 periods of surface-runoff from June, 1934, to September, 1938, showed total soil-losses ranging from 0.44 to 8.3 tons per acre. During the same periods of runoff the suspended-sediment load of the East and West Tarkio Creek Drainage-Areas, within which the station is located, averaged 17.3 tons per acre. In fact, during 32 storms the plots showed no soil-loss but the streams transported 672,000 tons of material out of the drainage-areas. On the other hand, soil-losses on watershed-plots of two to three acres at the La Crosse, Wisconsin, Conservation Experiment Station during 116 periods of runoff from April, 1934, to November, 1938, ranged from three tons per acre for unterraced pasture to 263 tons per acre for cultivated land. For the same periods of runoff the adjacent Coon Creek and Little La Crosse River carried a suspended load of 5.7 tons per acre, far below an average based on application of plot-measurements in proportion to land use in their drainage-areas.

Where such data show that erosion-losses are less than stream-load, this implies that there are important sources of erosional debris other than the farm land sampled by the plots. Study of the Tarkio Creek Area discloses that stream-bank erosion can account for the excess of sediment-load. Where stream-load is only a fraction of erosion measured on the land, it is obvious that large quantities of eroded material must be stopping on gentler slopes and flood-plains. Measurements in Coon Creek Valley disclose that 4,500 to 5,000 acre-feet of sediment has been deposited in it since accelerated erosion began, and this does not include large additional amounts in tributary valleys and upland swales.

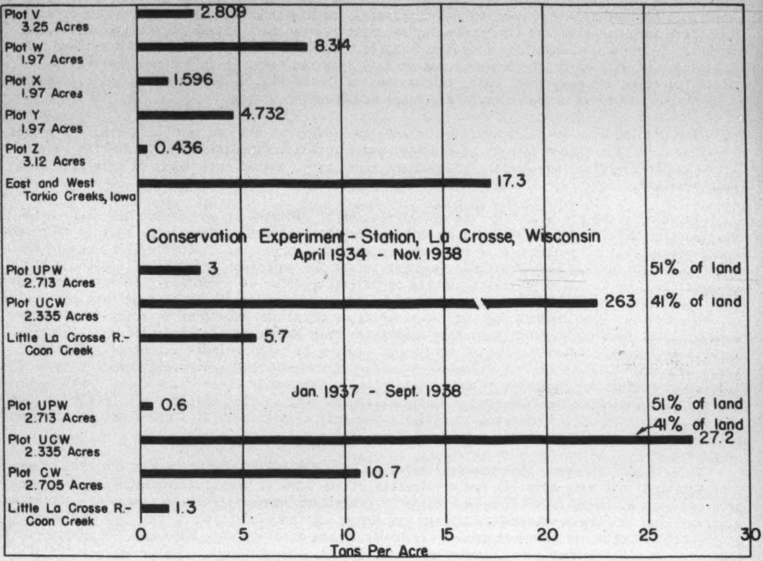

Fig. 4--Soil-losses versus sediment-load, Conservation Experiment Station, Clarinda, Iowa, June, 1934, to September, 1938

Sedimentation-studies thus not only give us a check on our erosion-measurements, but what is more important, they give us a basis for planning the control of erosion in accordance with its effects, not only on the land which loses the soil, but on the points downstream that are affected by erosional waste.

Research in sedimentation is still in its early stages. We still have many techniques to develop, for example, simple methods for measurement of bed-load movement on any stream, and we still lack an understanding of many of the laws of sediment-transportation and thus are prevented from developing the most effective control-measures, for example, measures to reverse the cycle of valley-trenching or arroyo development, especially in the Southwest, and initiate instead a process of valley-aggradation. We have before us the challenge not only to protect the huge public investments already made in such enterprizes as storage-reservoirs, irrigation-systems, and navigable waterways, but also to plan for adequate conservation of--as we plan to build--similar future developments.

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DISCUSSION

LORENZ G. STRAUB (University of Minnesota, Minneapolis, Minnesota)--This paper is timely in emphasizing the economic importance of soil-erosion which, until comparatively recently, has received far too little consideration. Instances may be cited where costly reservoirs have become practically valueless within a period of very few years in consequence of the unanticipated sedimentary loads of streams from which they received their water-supply. The author points out three factors influencing the rate of silting of reservoirs. The importance of a complete perspective of the situation for each projected reservoir cannot be too strongly emphasized. A generalization of the problem, however, can lead to erroneous conclusions.

Rivers of otherwise similar runoff- and discharge-characteristics as far as water is concerned are found to differ markedly from one another because of the differences in their sedimentary characteristics. The erosion from the drainage-area is of special importance in this connection. A number of factors are influential in producing erosion. Alternate freezing and thawing of saturated rock and soil, wind-action, and the dynamic action of rain combine in varying degrees in the processes of eroding the surface of the ground. Particles which have been loosened are transported by surface-runoff. The greater the velocity of the water, the greater will be the capacity to transport solid particles; moreover, the greater the intensity and duration of the rainfall, the higher will be the percentage of runoff.

Many types of erosion with their varied influences are observable. Several modes of erosion are more or less distinguishable from one another. Thus, in the source-district, the sedimentary load of the river consists largely of detritus formed by the weathering and wearing down of mountains. The river-slopes are steep and water flows at torrential velocities, at least during high stages. Following cloudbursts, detritus-avalanches take place; the streams then move great quantities of rock toward the sedimentary cone. For example, in the headwaters-area in the Los Angeles County Flood-Control District, debris-basins have been constructed to intercept the detritus-flows. After a single storm such debris-basins frequently become filled and must be excavated to be of further use. In some regions boulders a foot or more in diameter are rolled long distances with the finer gravel apparently forming a lubricating medium for the larger boulders.

Contrasted to the avalanches and detritus-transportation of torrential rivers, the soil-erosion in plains country, although often just as devastating, ordinarily takes place as a more gradual process. The seriousness of this type of erosion, which might be further classified into sheet-erosion and gullying, has been pointed out particularly in its possible influence upon the filling up of reservoirs. The need of taking into account the relative volume of the reservoir to the size of the drainage-area from which it receives its supply, as pointed out by the author, is especially to be emphasized. Other factors, of course, are also of importance, and, in some instances, may become a paramount consideration in the planning of a reservoir.

Twelve years ago the writer had occasion to undertake for the United States Engineer Department extensive studies of the sedimentary characteristics of many midwestern rivers forming, particularly, the Missouri River System. The great differences in the characteristics of these rivers from one another is especially interesting. Space will allow for only a few pertinent remarks regarding these observations.

The Missouri River is generally known to carry extremely high sedimentary loads. Erosion is certainly very serious in some regions. Yet, little significance can be attached to a mere statement of the average rate of erosion as determined from silt-observations. For example, during a two-year period of higher than average runoff from the Missouri River Basin, the average annual erosion amounted to only 0.0031 inch from the drainage-area. At the same time, based upon studies made on small plots of land, the average erosion was found to be many times this amount. In general, only a small percentage of the material moved continues a complete circuit to the river. To obtain some idea of the great variation in sediment actually carried by the river, Table 1 for a number of tributaries of the Missouri River Basin is of interest. These data are based entirely upon the suspended-sediment discharge observations; the bed-load is not

Table 1--Rate of erosion from various sections of Missouri River Drainage-Basin, July 1, 1929, to June 30, 1931

River	Area of Basin in square miles	Point of observation of silt-discharge		Annual silt-discharge in tons per square mile	Per cent of average for drainage-area above Kansas City
		Station	Mile above mouth Missouri River		
Missouri and tributaries above Fort Benton.....	24,570	Fort Benton, Montana........	2,211.8	24	9
Marias..................	9,160	Loma, Montana..............	2,190.4	36	13
Musselshell.............	9,570	Mosby, Montana.............	2,063.6	15	6
Milk....................	23,800	Nashua, Montana............	1,888.3	22	8
Yellowstone.............	70,400	Glendive, Montana..........	1,782.0	454	170
Little Missouri.........	9,500	Medora, North Dakota.......	1,703.6	208	78
Cannonball..............	4,300	Timmer, North Dakota.......	1,379.7	111	41
Grand...................	5,700	Wakpala, North Dakota......	1,266.5	92	34
Moreau..................	5,400	Promise, South Dakota......	1,273.4	104	39
Cheyenne................	25,500	Carlin, South Dakota.......	1,209.7	287	107
Bad.....................	3,120	Fort Pierre, South Dakota...	1,130.3	1,640	612
White...................	10,200	Oacoma, South Dakota.......	1,011.1	999	372
Niobrara................	13,000	Verdel, Nebraska...........	908.7	63	24
James...................	22,100	Scotland, South Dakota.....	876.5	1	0.4
Big Sioux...............	9,415	Akron, Iowa................	825.2	20	7
Little Sioux............	4,260	Correctionville, Iowa......	808.3	53	20
Platte..................	90,200	Plattsmouth, Nebraska......	616.0	145	54
Kansas..................	61,440	Bonner Springs, Kansas.....	401.9	235	88
Grand...................	7,900	Sumner, Missouri...........	293.8	848	316
Osage...................	15,300	Bagnell, Missouri..........	203.6	54	20
Gasconade...............	3,600	Rich Fountain, Missouri....	158.4	46	17

included. The wide deviation of different drainage-basins from one another is noteworthy. Comparing, for example, the silt-load of two streams within the Missouri River Drainage-Basin, having similar size drainage-areas, the Big Sioux with an area of 9,415 square miles, and the Grand River with an area of 7,900 square miles; the first has been observed during the period of observation to have an average suspended load of 20 tons per square mile while the latter was observed to have a load of 848 tons per square mile. Thus the ratio of the sedimentary loads was approximately 42 to 1. As compared to the average for the Missouri River Drainage-Area, the per cent per square mile was found to be only 0.4 per cent for the James River as compared to over 600 per cent for the Bad River.

There is some question in the writer's mind as to the validity of the statement frequently made that "more sedimentary material is swept into our large rivers and out into the ocean at present than before white men had settled over the plains areas." It is true that serious localized erosion has occurred because of extensive agricultural activity pursued without thought of protecting the soil from erosion, but the increased load in suspension in our main rivers probably has not changed greatly. A specific comparison is obtained by observations of the writer made in 1929-31 in relation to observations made in 1879 by James Seddon. Seddon made careful observations of the amount of suspended load transported by the Missouri River past St. Charles, Missouri, a point about 30 miles upstream of the river's mouth. The results of his observations were converted to the same units as used by the writer in connection with the studies on the Missouri River in 1929-31. The writer's observations were made on the river at a point about five miles upstream of where Seddon made his measurements. The agreement of the two series of investigations--1879 and 1930--despite the fact that Seddon's data were compiled at a time when doubtless there was much less agricultural development in the Missouri Basin, was surprisingly close; in fact, two independent suspended-load discharge rating-curves for the two periods very nearly coincided. One might conclude, therefore, that the quantity of suspended material transported by the Missouri River had not been greatly influenced by agricultural development. It is probably quite true that in many regions of the drainage-area the layer of fertile soil is being severely eroded; however, compared to the total suspended load of the Missouri, the additional material which is being washed directly into the river in recent years because of agricultural development is not appreciable.

Table 2--Comparison of bed-load and suspended load of tributaries of the Missouri River, July 1, 1929, to June 30, 1931

River	Bed-load		Suspended load		Ratio of suspended load to bed-load
	Tons	P.p.m.[1]	Tons	P.p.m.[1]	
Gasconade........................	34,900	9	293,000	77	8.4 to 1
Osage........................	15,700	3	1,505,000	281	96.0 to 1
Grand........................	740,000	186	11,560,000	2,910	15.6 to 1
Kansas........................	370,000	41	28,780,000	3,210	77.8 to 1
Platte........................	11,500,000	895	26,140,000	2,040	2.27 to 1
Niobrara........................	6,000,000	2,120	1,551,000	549	0.26 to 1
White........................	192,000	199	20,380,000	21,120	106.1 to 1
Cheyenne........................	700,000	456	14,100,000	9,180	20.1 to 1
Milk........................	5,900	9	1,065,000	1,680	180.5 to 1

[1] Referred to water; that is, 1,000,000 (weight of water).

There is a wide variation in the relation of suspended load to bed-load of various rivers. In most instances the suspended load is probably considerably greater than the bed-load. Again referring to midwestern rivers which are tributary to the Missouri River, Table 2 is presented of the relation of suspended load to bed-load. In these figures the suspended load is based upon daily observation of the water-discharge and suspended-load concentration. The bed-load is based upon mechanical analysis of specimens taken from the stream-bed at various points and a computation based upon laboratory experiments on sediment of various grades and the hydraulic characteristics of the river, including slope, relative roughness, and variation in discharge. These studies are based upon the period extending from July 1, 1929, to June 30, 1931. For a different period than the one used in this comparison, the ratio of suspended load to bed-load would be different, inasmuch as the amount of material transported by the two methods follow very different laws. Of the streams investigated, the Milk River apparently transported the least amount of material along its bed in comparison to that carried in suspension, the ratio of suspended load to bed-load being 181 to 1 for the two-year period ending June 30, 1931. This is because the Milk River has its bed composed primarily of very coarse material, the average size of particle being about 6.1 mm. The computed bed-load averaged only nine parts per million while the suspended load based upon field observations amounted to 1,680 parts per million.

On the other hand, the Niobrara River, judged from suspended-sediment observation, would be classified among the light-silt carriers of the plains area; however, the bed-load of this stream is very much greater than the suspended load so that its total sedimentary load is quite large. The stream is notorious for the rapidity with which it fills reservoirs with sediment, the material being made up, largely, of fine sand carried along or near the stream's bed. The average size of the stream-bed particle was found to be 0.285 mm. On this river the bed-load appears to be about 400 per cent of the suspended load, as compared to the Milk River where the bed-load is only about 0.5 per cent of the suspended load.

Conditions such as those described above must frequently be considered in planning reservoirs. Thus, for example, in the case of a small reservoir having a low dam; even though the suspended load is quite large, the reservoir will not necessarily become silted up. During high stages, when the dam does not serve to appreciably retard the flow, but rather approaches the situation of a submerged sill, the reservoir may become largely scoured out and relieved of much of the deposit left during low-water periods. Such a situation has been noted on the Kansas River in connection with a dam constructed at Lawrence, Kansas, many years ago. During high flows of the river, this dam becomes submerged and has little influence upon the normal flow of the stream, while during low water there is provided a reservoir of considerable capacity. Based upon observations and the analysis previously mentioned, the average bed-load of the Kansas River appears to be only about one or two per cent of the suspended load. In the case of a reservoir on the Niobrara at Valentine, on the other hand, sluicing operations have been found necessary quite frequently--at least about once a week--because of the heavy bed-load. Even with the aid of this operation, the reservoir remains quite definitely filled with the exception of a rather small area in the vicinity immediately upstream of the large sluiceways.

VITO A. VANONI (Cooperative Laboratory, Soil Conservation Service and California Institute of Technology, Pasadena, California)--Mr. Brown has outlined some results of experiments which I would like to discuss further. The experiments were made in a flume 60 feet long, 33-1/4 inches wide, with flows up to seven inches deep. The objective of the research was to study the mechanics of sediment-transportation and in this connection any effects that the sediment may have upon the flow-characteristics are of interest. One of the first effects noted was that the addition of a suspended load to a clear flow caused the velocity to increase.

Figure 1 shows velocity-profile curves for two flows of the same depth, one with clear water and the other with a suspended load whose distribution is shown at the right. The shaded area between the velocity-curves represents the increase in velocity. Since the flows have identical depths and slopes, the driving forces in the two cases are equal. Apparently the effect of the sediment is to reduce the friction-factor, thus requiring a greater velocity to produce a resistance which is in equilibrium with the fixed driving force. However, if the effect of the sediment were merely to reduce the channel-friction, it would be expected that the two velocity-curves would be parallel and displaced by a constant amount. That this is not the case is evident from Figure 1 and a different explanation must be sought.

Eddy-motion or turbulence is responsible for transmitting to the interior of the flow the retarding force arising at the boundaries, by giving rise to the so-called eddy-viscosity, which can be expressed by the momentum-transfer coefficient. The sediment in the flow must be suspended by the eddies and will tend to oppose their motion and to reduce their intensity. The eddies thus damped are less effective in transmitting the force and a higher velocity results. Experiments show that this damping depends on the amount and size of material in suspension.

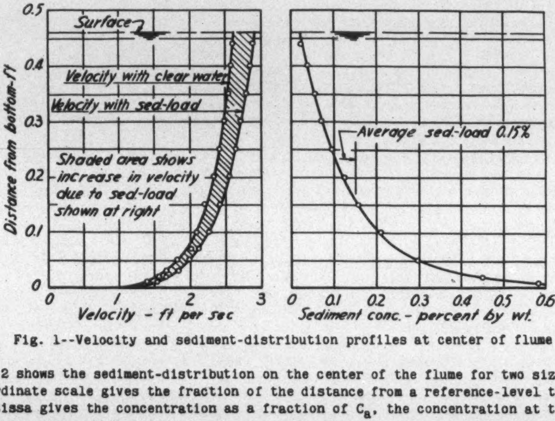

Fig. 1--Velocity and sediment-distribution profiles at center of flume

Figure 2 shows the sediment-distribution on the center of the flume for two sizes of material. The ordinate scale gives the fraction of the distance from a reference-level to the surface and the abscissa gives the concentration as a fraction of C_a, the concentration at the reference-level. The two curves at the right are for a sediment having a mean size of 0.100 mm. The solid line has been fitted to the experimental points, while the broken line shows the theoretical distribution according to the equation appearing at the upper right. It will be seen that in this case the theory shows a smaller relative concentration than was measured experimentally. It will also be seen that the experimental and theoretical curves have the same shape. Curves of this shape fitted the data very well in all cases. The curve at the left for a 0.160-mm sediment shows the striking result that the theory and experiments agree precisely. Experiments with material of intermediate size showed the same trend as with the fine material.

In order to explain this peculiar discrepancy it is necessary to examine closely the basis of the theory. Eddies transmit the resistance-force of the boundaries by a continual interchange of fluid between adjacent levels. This interchange, which can be expressed in terms of the eddy-viscosity, is also responsible for the upward transport of the sediment and the rate of transport can be expressed in terms of a transfer-coefficient similar to the eddy-viscosity. In developing the theory the assumption was made that the coefficients of eddy-viscosity and sediment-transport were equal. Figure 2 indicates that this is not the case, although the fact that the experimental data can be fitted by a curve of the same shape as the theoretical curve indicates a similarity between the mechanisms for transfer of sediment and force.

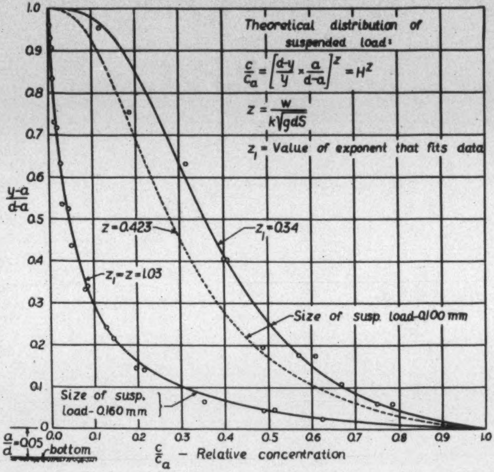

Fig. 2--Experimental and theoretical sediment-distribution at center of flume (d = depth of flow; y = variable distance from bottom; a = 0.05d = reference-level; C = variable sediment-concentration; C_a = sediment-concentration at reference-level; w = settling velocity of sediment in still water; k = universal constant; g = acceleration of gravity; S = slope of channel)

It is known that all components of turbulence are not effective in transferring force. However, these same components that do not transmit force and therefore are not accounted for in the theory, can transfer sediment. This idea may be used to explain why the observed concentration is greater than that shown by the theory. But, it does not explain the complete agreement between the theory and experiment observed for the coarse material. A second effect must account for this fact. Turbulence is made up of components of varying intensity, all of which may be effective in supporting fine material. However, as the sediment becomes coarser the weaker components are less able to support material, and since this effect is not taken into account by the theory, the actual concentration will tend to be less than the theoretical value.

Thus, it is seen that there are apparently two effects tending to modify the results given by the theory. One of these tends to increase the concentration, while the other tends to reduce it. If these ideas are correct then it can be concluded that the two effects were balanced for the case of the coarse sediment used in the above experiment. Also, on this basis, it can be predicted that for still coarser material the experimental concentrations would be less than those given by the present theory.

The full practical significance of these experimental results is not yet clear. However, it is possible to outline some of their important implications. To begin with, it is clear that the present theory for distribution of suspended load gives only approximate results and therefore must be revised. Because sediment damps the turbulence, it is expected that the presence of even a small amount in a flow reduces the additional quantity of coarse material and probably even of the finer material that can be carried. Although a stream carrying sediment will flow faster than a comparable clear one, it does not follow that an increase in erosive power will result. This will, of course, not apply to cases such as meanders and bends where the momentum of the entire stream is effective in eroding.

PHYSIOGRAPHIC ENGINEERING: LAND-EROSION CONTROLS

W. C. Lowdermilk

Peoples and civilizations write their records in the land. The scale of this writing is small in comparison with that of geophysical forces which have written a marvelous record in the Earth; nevertheless, its effects may mean life or death of peoples and rise or decline of civilizations. Land-erosion in Northern Syria proved to be in the end more devastating than war. Land-erosion has become a menace to national welfare and a vital problem of national economy of the United States. Only a beginning has been made in the present movement for land-conservation.

To establish an enduring and adequate agriculture in this new land of America confronts us with complex problems of which basic ones are geophysical. A guiding principle in applying findings of geophysical science is to set the stage in the use of land so that natural forces work for us rather than against us.

Land-erosion by wind and by water has been discussed in this symposium by Sharpe [see 11 of "References" at end of paper], Bailey [1], Malina [9], Yoder and Schiff [10], Carl Brown [2], and by others. Wind-erosion, about which we do not yet know enough, is spectacular but is not so widespread as water-erosion. Land-erosion by water is the most urgent physical problem in the use of land in the United States and commands our attention in the limited time allotted this discussion.

Surveys by the writer of land under use through the centuries in China, Korea, North Africa, Southern Europe, the Near East, England, and in the United States lead to the conclusion that tillers of soil have found throughout the ages that flat lands are least subject, and sloping lands are most subject to accelerated erosion by water. For this reason, tillers of soil have encountered their greatest difficulty throughout 7,000 years of farming in establishing an enduring agriculture on sloping lands. As flat alluvial lands proved too limited to supply growing populations, cultivation lines were pushed up slopes of hills and mountains into increasing hazards of accelerated soil-erosion on steeper and steeper slopes. The land of ancient Phoenicia--the present-day Lebanon--bears record of just this extension of farming up slopes of Lebanon and Anti-Lebanon Mountains. Failures interspersed with a few remarkable successes in slope-farming only emphasize the problem and cost of permanent agriculture on sloping lands.

Agriculture in the United States is confronted with this same age-old problem of slope-cultivation. Our flat lands of about 62 million acres of low erosion-hazard but with lesser problems of drainage, irrigation, and stream-bank erosion, are far too limited for our needs. Most of farm crops must be grown on sloping lands of about 300 million acres now under cultivation, where hazards of accelerated erosion vary from place to place with climate and slope, soils and cropping. Solutions of this problem call for basic physical measures that may be grouped under three headings: First, contour-farming; second, bench-terracing; and third, stream base-level control. Control of wind-erosion and measures of irrigation also have their place in land-conservation but are more particularly applicable to flat lands. The physical measures applicable to sloping lands of humid and semi-humid climate require support of appropriate land-management and soil-improvement practices, which are beyond the scope of this discussion. The key problem of land-conservation is to safeguard slopes from soil-wastage under necessary cultivation and use. Conservation of the physical body of soil-resources takes first place to assure liberty of action in the use of land, choice in kinds and types of crops and in degree of improvement; for when the soil is gone, all is gone.

Contour-farming is the first measure of physiographic engineering and, unlike straight-line farming, is designed to set the stage on cultivated lands so that natural forces will work for land-conservation rather than against it. Contour-farming embraces coordinated measures carried out on the level or near level across and around slopes. Measures applicable to plowed lands include contour-cultivation, contour-strip cropping, and broad base-terracing; those applicable to range- and forest-lands include contour-furrows, cross-slope diversions, and water-spreading. These measures are designed to retard overland flow, and finally to lead storm-waters in low-gradient channels across slopes to prepared outlet waterways which in turn guide wild waters harmlessly into natural drainage-channels. The more fully are principles of hydrology known, the more successful will the application of such measures be.

Physical measures of control need to be supported by appropriate agronomic, soil-improvement, and range- and forest-management practices to increase intake capacities and infiltration-rates of soils. Recent findings of Duley and Russell [3], for example, disclose that crop litter ("stubble mulch") has the same order of influence as the writer [6] found forest-litter to have

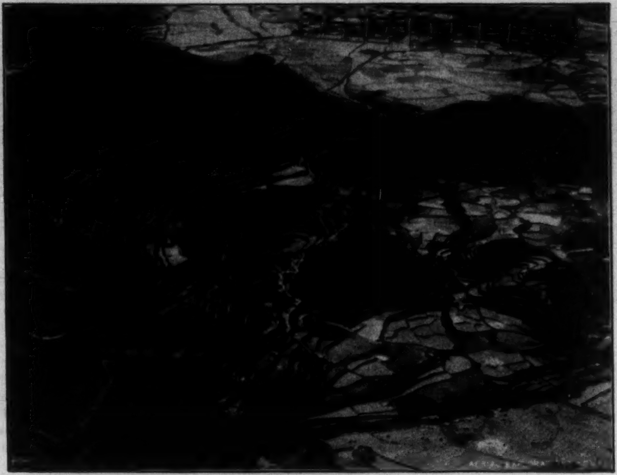

Fig. 1--An aerial photograph taken by the Shippee-Johnson Exploration in Peru showing bench-terracing employed by the Incas or pre-Incas in converting steep mountain slopes into flattened farm fields; benching has been brought about by construction of stone walls and by strips of natural vegetation (Courtesy of Aerial Explorations, Inc., New York City)

Fig. 2

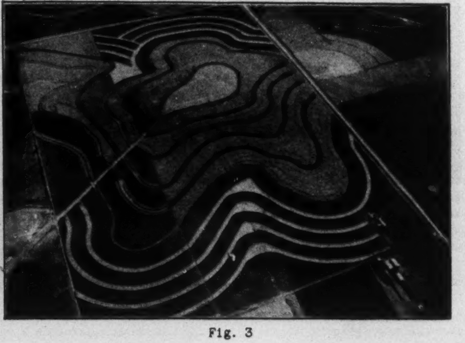

Fig. 3

Fig. 2--Bench-terracing by means of rock walls on the contour (This method of flattening sloping lands for sustained agriculture was developed by the Phoenicians; these fields doubtless have been under cultivation for 4,000 years or more)

Fig. 3--Aerial view of contour-farming as a measure of physiographic engineering involving strip-cropping and broad-base terrace outlet-channels supported by appropriate soil-improvement and agronomic measures

on infiltration of rain-water and control of soil-erosion. Tillage-practices to make use of crop-litter may protect cultivated land on slopes of five per cent and more, varying with climate and soil. The measure may safeguard cultivated land of steeper gradients than has hitherto been found possible by other means.

Fig. 4--Bench-terraces in Puerto Rico formed by planting strips of heavy grasses on the contour and plowing down slope (These benches as they stand were flattened after four plowings, representing two years of farming; the bank of the bench is now about three feet high; the usual variety of farm-crops produced in Puerto Rico are grown on the land)

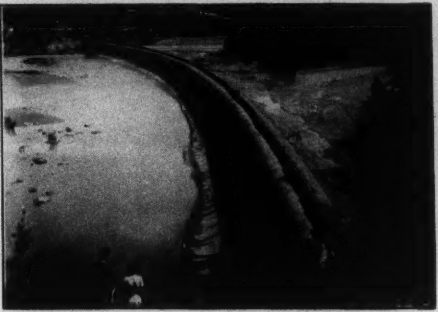

Fig. 5--View of the dam and power-house on Dan River at Schoolfield, Virginia, after complete drawdown showing silt heavily covered with vegetation reaching almost to the dam (In effect, this dam is establishing new base-levels of cutting and will in time reduce erosion-potentials upstream; this dam suggests a program in physiographic engineering to establish base-levels of stream cutting at strategic points)

Land above safe gradients for cultivation must be kept in perennial cover of grass or forest for its conservation unless slopes under cultivation are actually reduced to lower and safe gradients.

The second measure of physiographic engineering is designed to do just this--to reduce cultivated slopes to lower gradients. Construction of rock walls to bench sloping land, while effective in Lebanon and Peru [7], is economically impossible at modern wages in the United States, where rock is near at hand, but is all the more out of question in vast rolling lands devoid of rock. Some other method needs to be found if we must cultivate slopes with gradients normally above those safe for cultivation under contour-farming supported by use of crop-litter. Bench-terracing is proposed to meet this need; it includes practices not yet in common use in this new land of America and merits special consideration in physiographic engineering [8].

Methods of bench-terracing sloping land are time-honored and simple as the writer has found in many lands. Narrow strips of close-growing vegetation laid out on the contour and spaced on the slope bring about the desired flattening of cultivated strips. A two-way plow throws furrow-slices down slope; soil is gradually moved by plowing away from bases of up-slope vegetated strips and shifted down slope toward the vegetated strip next below. Down-slope movement of soil under plowing and wash of rain is benched against these contour vegetated strips. Cultivated strips flatten as benches and vegetated strips steepen as banks. Benches need not be level, but only to be reduced to gradients safe for sustained cultivation for a given climate, soil, and type of cropping. Cultivated benches are wide on gentle slopes, but become narrower as slope-gradients are steeper.

In this manner either by chance or by design slopes are converted into a series of bench-terraces of flattened benches and steepened banks. A variety of methods of plowing the benches determines rates of flattening. Vegetation of banks may be natural growth or specially sown perennial cover. These contour-vegetated banks become absorbent bands of storm overland-flow and checks of soil-movement across slopes. Excess waters may be drained off fields by cross slope-channels located along lower edges of vegetated banks into specially prepared waterways. Ordinarily, vegetated banks absorb overland flow in humid climates except in extraordinary storms.

Bench-terracing is limited obviously to slopes with moderately deep to deep soils, and is not suited to slopes of thin soils. Rarely, however, can cultivation on slopes of thin soils be justified for permanent agriculture. As soil moves down slope under action of plowing and wash of rain, top soil is worked off the upper half of a cultivated bench and accumulates and thickens on the lower half. Sub-soil may be exposed gradually on the upper part of benches. Objections to the measure on this ground can be met by soil-improvement and fertilization of freshly exposed ground to keep pace with down-slope movement of soil as well as by suitable plowing schedules. This is fully justified in conservation of the land. Narrow benches interfere with use of powered farm machinery, and are cited as other objections to bench-terracing. Nonetheless, if it comes down to a question of saving soil or investments in farm machinery, the vote must be cast for conservation of the soil.

Bench-terracing is not new; it has been used but unheralded chiefly in loessial as well as in residual soils of China for a thousand years or more. The practice was also found by the writer on the slopes of the French Pyrennees and on loessial slopes of Northeastern France, and has been variously explained by geographers [5]. Bench-terracing technically designed offers great promise as a measure of land-conservation. Bench-terracing is now being used locally in California orchards and is spreading in Puerto Rico as a measure of soil- and water-conservation. It is common throughout the United States to see benching of cultivated land against fences wherever they run by chance across slopes between cultivated fields. Bench-terracing embodies simple principles of physiographic engineering and is effective where the stage is set so that natural forces work for land-conservation in flattening sloping land to gradients safe for sustained cropping.

These two measures of contour-farming and bench-terracing apply primarily to slopes under cultivation where erosion-hazards are highest. The third measure of physiographic engineering has to do with control of base-levels of cutting by streams. Erosion-potentials within a drainage are influenced by local base-levels of cutting of streams [2]. Trenching by streams and gully-washers into former alluvial fill, for example, rejuvenates tributary streams. As head-cutting works up tributaries, measures of land- and soil-erosion control may be endangered or destroyed. Control of secondary base-levels of stream-cutting under certain conditions may be used as a long-range measure of land-erosion control, but is now generally overlooked in short-range projects.

More than this, rates of geological norms of land-erosion may be retarded by raising base-levels of stream-cutting at strategic points. Hundreds of instances occur throughout the United States in dams built to impound waters for power-, irrigation-, and flood-control, in the East and in the West [5]. We can foresee the time, as has already happened in many smaller reservoirs, that large reservoirs will silt up [2] and existing dams will be little more than great permanent check-dams, above which alluvial flats of eroded soils deposited to wasteful depths will be farmed to crops. As levels of alluvial fills move upstream, base-levels of tributaries are raised. We can imagine that land-forms such as are found above hard-rock dykes across valleys in nature will also develop above dams of silted reservoirs.

Grades of such alluvial fills are determined by textural size of fill-materials; the finer the material the flatter is the grade; the coarser the material the steeper is the grade [5]. If coarse material is supplied artificially to the stream it may be possible to steepen grades of fills so as to increase capacities of channels above dams to store erosional debris as a measure to control debris-floods. Continuation and enlargement of experimental studies on laws of entrainment and their application are urged as a measure of physiographic engineering. The possibility of steepening grades of alluvial fills by some such measure suggests further ways of raising base-levels of cutting of tributary streams with corresponding effects in reducing erosional potentials within tributary drainages. Control of local base-levels of stream-cutting such as is brought about by construction of dams for other purposes may well become a specific reason for construction of new multiple-purpose dams or even construction of control-sills and soil-saving dams as long-range measures in land-erosion controls necessary to safeguard measures of soil-conservation of land-surfaces.

Summary--Land-erosion controls call into use physical measures of physiographic engineering which set the stage for natural forces to work for rather than against conservation of land. Physical measures must be supported by agronomic and soil-science for a fully coordinated plan of land-conservation. Physical measures for safeguarding sloping lands are combined into three groups, namely, contour-farming, bench-terracing, and stream base-level control for long-range control of land-erosion.

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Soil Conservation Service,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30 – MAY 3, 1941

SECTION OF GEODESY

REPORTS AND PAPERS

WASHINGTON, D C.
MAY 2, 1941

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REPORTS AND PAPERS SECTION OF GEODESY
NATIONAL ACADEMY AND RESEARCH COUNCIL BUILDING
9:00 A.M., May 2, 1941

THE INTERNATIONAL ASSOCIATION OF GEODESY

Walter D. Lambert

The war has brought international geodetic activities almost to a standstill.

The composition of the Executive Committee of the International Association of Geodesy at the time of the Washington Assembly was as follows:

Office	Name	Country	Expiration of term
President	F. A. Vening Meinesz	Holland	1939
Vice-President	E. Soler	Italy	1942
Vice-President	W. D. Lambert	United States	1939
Secretary	G. Perrier	France	1942
Member-at-large	K. S. Klingenberg	Norway	1942
Member-at-large	J. Maury	Belgium	1942
Member-at-large	N. MacLeod	Great Britain	1939
Member-at-large	K. Weigel	Poland	1939

In accordance with the agreement at Washington no elections were held; the incumbent officers all hold over until their successors can be elected.

Professor Soler died in 1940 and most of the remaining members of the Committee are in occupied territory. General MacLeod and I are the only members free to act. Thus any action that may be taken by a few members will be technically irregular and can be validated only on the plea of compelling necessity.

The regular publications of the International Association of Geodesy are: The Bulletin Géodésique, issued quarterly; the national reports, issued triennially in connection with the general assemblies; the general reports, also issued in connection with the general assemblies.

The Bulletin Géodésique has been carried as far as No. 62, which is for April-May-June, 1939. This number contains the program for the Washington Meeting. General Perrier brought with him to Washington a supply of this number in a preliminary edition. Recently copies of the definitive edition have been received in Washington.

The national reports of the member countries cover the geodetic activities in each country during the preceding triennial period. Each country prepares and prints its own report and supplies 1,100 copies to the Secretary. The Secretary binds the various reports into one or more volumes, provides a cover and an index, and distributes the volumes to the member countries. The national reports were duly sent to Paris but it has not been possible to assemble and distribute them.

The general reports are really stated special reports on geodetic subjects. They are numbered from 1 to 9, but some reports are subdivided, so there are 12 reports in all. Many of these 12 subjects were passed over entirely by the Washington Meeting, and of the reports taken up only a few are available in printed or mimeographed form.

General Perrier brought with him to Washington a printed volume of his general report on bases covering the years 1912-35. Very few copies of this are available in the United States.

Dr. Heiskanen presented in preliminary form a report on isostasy. A few copies of the definitive report in mimeographed form were afterwards sent to this country.

The report on earth-tides, which I prepared, has been printed as a special publication of the Coast and Geodetic Survey.

Dr. de Graaff Hunter prepared a report on the deflections of the vertical. A few mimeographed copies were available. A part of the supplementary collection of numerical data (not included in the mimeographed report) would have been the deflections of the vertical in the United States. These are being assembled and discussed at the United States Coast and Geodetic Survey and it is expected that they eventually will be published.

The International Association of Geodesy has undertaken to issue a triennial bibliography of geodesy but the publication had hardly become established as regular at the time of the Washington Meeting. A second volume was published in 1938, covering the years 1931-34, inclusive. Only a very few copies are in this country.

The proceedings of the Association of Geodesy at Washington would normally be published in the Bulletin Géodésique, but since it is unlikely that publication will soon be resumed, it seems desirable to issue a special publication giving the day-to-day proceedings of the Association of Geodesy at the Washington Meeting, together with some account of other activities. It is hoped that some of the money collected for the expenses of the Washington Assembly will be available for the purpose.

One international scientific activity that has been comparatively little affected by the war is the International Latitude Service. The discussion of current work is kept nearly up to date but no comprehensive discussions have been published recently.

Because of the war we hear little from our friends abroad. Early in the year Commander Garner received a letter from our President, Dr. F. A. Vening Meinesz. It was written from his usual address. The letter asked about the results from a gravity-at-sea expedition and indicated that Dr. Vening Meinesz was at his usual address in Holland. Beyond that it gave no information. No further word has been received from him.

Our Secretary, General Perrier, remained in Paris except for two trips of a month each to Lyons, in unoccupied France, to give a course of lectures. Communication with him is very slow but seems fairly certain. At latest accounts the work of the Secretary's office was being carried on with a much reduced personnel.

A letter dated March 18, 1941, has been received from Professor Heiskanen at Helsinki. In spite of unfavorable conditions the Isostatic Institute is continuing work. Three publications have been completed recently and three more are under way. Professor Heiskanen would doubtless be glad to receive letters from his friends.

Word from the Jollys at Southampton indicates that they are well and cheerful in spite of the severe punishment that their home town has had to take.

This exhausts my budget of personal news from friends abroad.

U. S. Coast and Geodetic Survey,
Washington, D. C.

A DETERMINATION OF ASTRONOMICAL REFRACTION FROM PHYSICAL DATA

John E. Willis

(1) Spherical coordinates of star-positions are used in measuring the positions of celestial objects, in determining time, and in determining longitudes and latitudes of points on the Earth's surface for the purposes of navigation and geodetic surveying.

One of the spherical coordinates, called right-ascension, analogous to longitude on the Earth, is measured by using the rotating Earth and the moments of transits of the stars past a mechanically established plane, the rotating Earth marking off equal intervals of right-ascension in equal intervals of time.

The other spherical coordinate, called declination, analogous to latitude on the Earth, is usually measured by the use of divided circles placed in the plane of the meridian.

The apparent positions of the stars are affected by refraction of star-light in passing through the atmosphere of the Earth. The wave-fronts of the beams of light are delayed in proportion to the amount of material passed. The accidental irregularities of density of the atmosphere, due principally to irregularities of temperature and pressure, are the principal cause of accidental error in the accurate measurement of positions of stars, and the systematic properties of the atmosphere must be taken into account in deducing the true positions of the stars.

The most obvious systematic effect of the atmosphere is that which causes the stars to be observed nearer the zenith than they would be if there were no atmosphere, since the lower parts of the beams are delayed more than the upper parts. This change of position is known as astronomical refraction.

When the positions of stars are determined from observations in the meridian, only the declinations need correction for astronomical refraction. Although there are several schemes in prospect for the determination of declinations without the necessity for accurate computation of the whole astronomical refraction, it is likely that for many years to come the evaluation of this refraction will continue to be an essential part of the determination of star-positions.

(2) If the curvature of the Earth's surface is neglected, astronomical refraction is equal to the refractivity of the local air multiplied by the tangent of the zenith-distance. If the curvature is not neglected, the refraction-computation involves quantities representing the refractivity of the air at all heights; and the loci of equal refractivity are assumed to be concentric spherical surfaces.

(3) With increasing understanding of the physical structure of the atmosphere, various systems for the computation of astronomical refraction have been developed. When known physical data included only the rate of change of temperature with height in the lower atmosphere, it was necessary to analyze the circumpolar observations of star-declinations for the coefficients representing local refractivity, variation with temperature, and the effects of the unknown state of the upper atmosphere, while the effect of the variable amount of water-vapor was represented only by modification of the temperature-coefficient although the effect is not a linear function of the temperature.

(4) With a principal interest in spectrum analysis, laboratory physicists for more than 50 years have pursued with increasing success the accurate determination of the local refractivity and its variation with water-vapor content and with temperature and wave-length. Their measures, with the extension of meteorological knowledge into the regions of the stratosphere, and with the realization of the reasonableness of the continuance of the substantially constant temperature of the stratosphere to the limits of perceptible refractivity, seem to provide the foundation for a system for the computation of astronomical refraction, perhaps entirely adequate to satisfy the needs of practical astronomy, without involving star-observations themselves in a first-order relation in the evaluation of any of the critical constants.

The refraction-equation

(5) We may consider the atmosphere above an observer to be composed of a great many concentric layers of air of different indices of refraction, n_0 (beginning with the lowest layer), n_1, n_2, . . n , ., with radii of curvature at the lower boundaries of the layers, r_0, r_1, r_2, .. r , . . A light-ray is traced from the observer at point P_0, having an angular zenith-distance of z at the point P_0 and zenith-distances (angles between the ray and the lines to C, the center of curvature of the layers) i_1, i_2, . . i , ., in the successive layers at their lower boundaries at points P_1, P_2, . . P , . .

In the plane established by the ray and the center of curvature, in triangle CP_0P_1

$$r_0 \sin z = r_1 \sin P_0P_1C \tag{1}$$

From optics,

$$n_1 \sin i_1 = n_0 \sin P_0P_1C \tag{2}$$

Eliminating $\sin P_0P_1C$ from equations (1) and (2), we get

$$n_1r_1 \sin i_1 = n_0r_0 \sin z \tag{3}$$

Similarly,

$$n_2r_2 \sin i_2 = n_1r_1 \sin i_1$$

and, in general,

$$n\ r\ \sin i = n_0 r_0 \sin z \tag{4}$$

Equation (2) may be transformed into

$$(n_1 + n_0) \tan [(i_1 - P_0P_1C)/2] = - (n_1 - n_0) \tan [(i_1 + P_0P_1C)/2] \tag{5}$$

which leads, when $(i_1 - P_0P_1C)$ approaches zero, to $n\ dR = dn \tan i$, or

$$dR = - \tan i\ dn/n = \tan i\ d \log n_0/n \tag{6}$$

in which R is the astronomical refraction.

Substituting the value of i from equation (4) into equation (6), and letting the quantity $[(nr/n_0r_0)^2 - 1]$ be represented by N, we get

$$dR = \sin z\ (\cos^2 z + N)^{-1/2}\ d \log n_0/n \tag{7}$$

or

$$dR = \tan z\ (1 + N \sec^2 z)^{-1/2}\ d \log n_0/n \tag{8}$$

Expanding, by the use of the binomial theorem, and indicating the integration, equation (8) leads to

$$R = \tan z \int [1 - (1/2)N \sec^2 z + (3/8)N^2 \sec^4 z - \ldots]\ d \log n_0/n \tag{9}$$

This may be numerically integrated term by term over the whole or parts of the range of the atmosphere if we can find data to represent the relation between n and r. The resulting equation will be of the form

$$R = \tan z\ (\log n_0 + A \sec^2 z + B \sec^4 z + C \sec^6 z + \ldots) \tag{10}$$

or

$$R = \tan z \log n_0\ (1 + A' \sec^2 z + B' \sec^4 z + C' \sec^6 z + \ldots) \tag{11}$$

in which A, B, C, . . ., A', B', C', . . . are functions of the adopted atmospheric conditions. These equations permit the value of z to be selected after the determination of A, B, C, etc.

Or we may numerically integrate equation (7) for particular values of z.

The Earth's atmosphere

(6) Temperature-distribution in the atmosphere may be interpreted as the result of relations which are about as follows:

The Sun's radiation traverses pure dry air with but little absorption, although with considerable loss by scattering; the transmitted radiation is partly absorbed by the ground and by the lower humid and dust-laden atmosphere. The ground and the lower atmosphere then radiate relatively long wave-lengths because of the low temperature relative to the temperature of the Sun. The upper atmosphere absorbs part of this low-frequency radiation; and at the same time emits radiation at a rate which decreases with temperature and therefore with height.

The radiating ground and lower atmosphere, as seen from any point in the upper atmosphere, would appear to extend over nearly the same solid angle (nearly half of the total) and give radiation of intensity nearly the same at all heights for the points in the upper atmosphere; so that, at and above the height at which the space occupied by the atmosphere becomes nearly transparent to the radiations to and from the particles, the temperature becomes nearly constant with height, considerably above zero on the absolute scale.

Purely radiation-equilibrium does not hold over about the lower eight-tenths of the mass of the atmosphere because of the continual vertical convection and attendant dynamic temperature-changes; but the distribution of radiation and absorption is the cause of this also.

The diurnal variation of temperature in the free atmosphere rapidly diminishes with height to a value of the order of a fraction of 1° C at a few km.

Definite evidence exists that dry air is of uniform chemical composition up to heights greater than 20 km. It is probable that no substantial error in refractivity-calculations results from adopting the composition as uniform throughout.

Table A--Relation of temperatures to pressures in the atmosphere

(p/p_0)	(T/T_0) from equations (12),(13)	Observed, summer		Observed, winter		Observed, mean	
		(T/T_0)	(O-C)	(T/T_0)	(O-C)	(T/T_0)	(O-C)
1.0	1.000	1.000	.000	1.000	.000	1.000	.000
0.8	0.976	0.968	-.008	0.982	+.006	0.975	-.001
0.6	0.931	0.931	.000	0.938	+.007	0.934	+.003
0.4	0.865	0.863	-.002	0.862	-.003	0.862	-.003
0.2	0.778	0.767	-.011	0.787	+.009	0.777	-.001
0.1	0.778	0.772	-.006	0.785	+.007	0.778	.000
0.01	0.778	0.779	+.001	0.785	+.007	0.782	+.004

Therefore, it seems probable that the measured absolute temperature of a particle in the high atmosphere may be found to be simply related throughout the year to the absolute temperature of the effective radiating surface in the lower atmosphere if the particle remains at the same mass-height (that is, if the particle remains with the same fractions of the mass of the air below it and above it) throughout the year.

We find it possible to well represent relative temperature in the free air by a power series in the relative pressures, which are closely related to mass-heights. From the 3rd (1940) edition of Humphreys' "Physics of the Air" [pp. 61 and 80], we deduce

$$(T/T_0) = 0.670 + 0.5925\ (p/p_0) - 0.2625\ (p/p_0)^2 \qquad (12)$$

for (p/p_0) from 1.000 to 0.200, and

$$(T/T_0) = 0.778 \qquad (13)$$

for (p/p_0) from 0.200 to 0.000, T being absolute temperature and p being pressure, the subscript zero referring to conditions near the ground. These values for our adopted standard atmosphere are tabulated in Table A, with the departures of the data from them.

The predominance in Table A of negative residuals for summer and positive residuals for winter (average 0.004, equivalent to about 1° C) may be due to the effective radiating layer of moist air being farther from the ground in the summer than in the winter. This may be allowed for if desired, by the use of Table 7, or its effect may be avoided, along with the similar effect of non-standard diurnal variations of temperature in the lower atmosphere, by not observing stars at very large zenith-distances, that is, over 80°. Or the apparently systematic trend of the summer and winter residuals may even be due to accidental errors.

(7) By substituting equations (12) and (13) in the equation expressing the fact that the variation of pressure with height at any point is due to the variation of weight of air above that point, namely,

$$(r_0/r)^2\ d\ r/r_0 = -(\ell_0/r_0)(T/T_0)\ (p_0/p)\ d\ p/p_0 \qquad (14)$$

(in which ℓ_0 is the pressure-height of a homogeneous atmosphere of the density existing at the surface of the Earth where the pressure is p_0, the temperature is T_0, and the distance from the center of gravity is r_0), and integrating, we get

$$(r/r_0) = 1 - \left\{(\ell_0/r_0)[0.46125 - 1.542732 \log_{10}(p/p_0) - 0.5925\ (p/p_0) + 0.13125\ (p^2/p_0^2)]\right\} \qquad (15)$$

for (p/p_0) from 1.0 to 0.2, and

$$(r_0/r) = 1 - (\ell_0/r_0)\ [0.1741807 - 1.7914112 \log_{10}(p/p_0)] \qquad (16)$$

for (p/p_0) from 0.2 to 0.0.

Data for a representative state of the standard atmosphere are given in Table B, computed for latitude 45°, and for a temperature at the base of 10° C (50° F).

Table B--A representative state of the standard atmosphere

Relative pressure, (p/p_0)	Relative temperature, (T/T_0)	Temperature, °C	Temperature, °F	Height, $(r - r_0)$	
				km	miles
1.0	1.0000	+10.0	+50.0	0.0	0.0
0.5	0.9006	-18.1	- 0.6	5.5	3.4
0.25	0.8017	-46.1	-51.0	10.4	6.4
0.125	0.7780	-52.8	-63.1	14.9	9.2
0.0625	0.7780	-52.8	-63.1	19.4	12.0
0.03125	0.7780	-52.8	-63.1	23.9	14.8
0.015625	0.7780	-52.8	-63.1	28.4	17.6
0.001	0.7780	-52.8	-63.1	46.3	28.8
0.000001	0.7780	-52.8	-63.1	91.8	57.0

(8) For determining the values of A, B, C, etc., in equations (10) and (11), values of (T/T_0), (r_0/r), and eventually N and $\log_e (n_0/n)$ were computed for every 0.02 of (p/p_0) from 1.00 to 0.20, and for $0.2 \times 2^{0.0}$, $0.2 \times 2^{-0.2}$, $0.2 \times 2^{-0.4}$, etc., until $\log_e (n_0/n)$ became equal to $\log_e n_0$ to eight decimal places, using the following constants and equations in conjunction with those given above.

$$\left.\begin{aligned}
&(\ell_0/r_0) = 0.00128750 \quad n_0 = 1.00028201 \quad (1/n_0) = 0.99971807\\
&\log_e n_0 = (n_0 - 1) - (1/2)\,(n_0 - 1)^2 = 0.00028197\\
&(n/n_0) = (1/n_0) + (1 - 1/n_0)\,(p/p_0)\,(T_0/T)
\end{aligned}\right\} \qquad (17)$$

These constants were intended to represent effective wave-length 0.5808 micron, the latitude of Kiel, 54° 25', elevation 52 meters, temperature 7°48 C, barometer-height 754.48 mm reduced to temperature of 0° C, and vapor-pressure 4.22 mm, using data from Meggers and Peters [see 1 of "References" at end of paper].

(9) The values of $\log_e (n_0/n)$ were numerically differentiated and the derivatives with respect to the tabular intervals were multiplied by the numerical integration-coefficients, -1/24, 1/2, 25/24, 1, 1, . . ., 1, 1, 25/24, 1/2, -1/24, which correspond to a four-point representation in a power-series as a basis of integrating over a central interval. It was then only necessary to sum up the products of these numbers by the values of the appropriate powers of N, and to multiply the sums by the coefficients in equation (9) to obtain equation (18) where $a = (0.01 \sec^2 z)$.

$$\left.\begin{aligned}
\text{Refraction} = \tan z\, [(&+ .0002\,0947\,0 - .0000\,1355\,9\, a + .0000\,0198\,4\, a^2\\
&- .0000\,0038\,0\, a^3 + .0000\,0008\,3\, a^4 - .0000\,0002\,0\, a^5 + .0000\,0000\,5\, a^6\\
&- .0000\,0000\,1\, a^7 + .0000\,0000\,0\, a^8) + (.0000\,7250\,0 - .0000\,1888\,5\, a\\
&+ .0000\,0845\,4\, a^2 - .0000\,0497\,0\, a^3 + .0000\,0369\,0\, a^4 - .0000\,0338\,1\, a^5\\
&+ .0000\,0370\,9\, a^6 - .0000\,0471\,6\, a^7 + .0000\,0674\,1\, a^8)]\\
= \tan z\, [&+ .0000\,8197\,0 - .0000\,3244\,4\, a + .0000\,1043\,7\, a^2\\
&- .0000\,0534\,9\, a^3 + .0000\,0377\,4\, a^4 - .0000\,0340\,1\, a^5 + .0000\,0371\,4\, a^6\\
&- .0000\,0471\,8\, a^7 + .0000\,0674\,1\, a^8] \text{ expressed in radians}\\
= \tan z\, [&58.1605 - 6.6921\, a + 2.1528\, a^2 - 1.1034\, a^3 + 0.7783\, a^4\\
&- 0.7014\, a^5 + 0.7661\, a^6 - 0.9731\, a^7 + 1.3905\, a^8] \text{ expressed in seconds of arc}
\end{aligned}\right\} \qquad (18)$$

where the multipliers in the first parentheses within the brackets apply to the stratosphere and the multipliers in the second parentheses within the brackets apply through the stratosphere.

(10) The series was then modified so that it could be evaluated up to z = 85°, or so, by assuming that, as more terms are included, the departures of the successive subtotals from the true value which the series represents may be expressed in a power-series. This turned out to be the equivalent of taking successive means of subtotals. The result can also be obtained by the use of the series obtained by multiplying the successive coefficients of the powers of $a = (0.01 \sec^2 z)$ in equation (18) by the numbers 1.0000 000, 0.9921 875, 0.9375 000, 0.7734 375, 0.5000 000, 0.2265 625, 0.0625 000, 0.0078 125, and 0.0000 000, which have as differences the last set of numbers in the triangle resulting from taking means on a sort of Pascal's triangle:

							.0000 000
						.0000 00	
					.00000		.0078 125
				.0000		.0156 25	
			.000		.03125		.0546 875
		.00		.0625		.0937 50	
	.0		.125		.15625		.1640 625
0.0		.25		.2500		.2343 75	
	.5		.375		.31250		.2734 375
1.0		.50		.3750		.3125 00	
	.5		.375		.31250		.2734 375
0.0		.25		.2500		.2343 75	
	.0		.125		.15625		.1640 625
		.00		.0625		.0937 50	
			.000		.03125		.0546 875
				.0000		.0156 25	
					.00000		.0078 125
						.0000 00	
							.0000 000

This results in the expression

$$\left.\begin{aligned}\text{Refraction} = \tan z \log_e n_0 \,[1 &- .1150\;6232\;(0.01 \sec^2 z)\\ &+ .0367\;2629\;(0.01 \sec^2 z)^2\\ &- .0177\;8599\;(0.01 \sec^2 z)^3\\ &+ .0103\;5073\;(0.01 \sec^2 z)^4\\ &- .0060\;3005\;(0.01 \sec^2 z)^5\\ &+ .0029\;8434\;(0.01 \sec^2 z)^6\\ &- .0010\;4567\;(0.01 \sec^2 z)^7\\ &+ .0001\;8678\;(0.01 \sec^2 z)^8]\end{aligned}\right\} \qquad (19)$$

(11) In search of means for permitting the numerical coefficients of equation (19) to vary with varying values of (ℓ_0/r_0) to correspond to the different observatories at different latitudes and to correspond to the variations of (ℓ_0/r_0) with T_0, we note that the integral of $N\ d \log n_0/n$ between the limits n equals n_0 and n equals one, occurring in equation (9), can be shown to be nearly equal to

$$(1 - 1/n_0)\;[(1 - 1/n_0) - (2 + \ell_0/r_0 - 1 + 1/n_0) \int (p/p_0)\;(T_0/T)\;d\;r/r_0] \qquad (20)$$

in which the indicated integral used over the range of the atmosphere is equal to the mass-height of the atmosphere, or nearly equal to the pressure-height, which can be measured at the observatory. Since the pressure is caused by the mass of the atmosphere affected by the diminution of gravity with height (about one part in 400 at eight km above the ground), it is not strictly correct to say that the practical coefficient of the $(\sec^2 z)$-term in the astronomical refraction is independent of the law to be adopted for the distribution of material in the atmosphere. Compare Newcomb's Compendium of spherical astronomy [p. 213]. However, an approximation of the mass-height is obtained by multiplying the pressure-height by $(1 + \ell_0/r_0)^2$ or $(1 + 2\,\ell_0/r_0)$. The coefficient of $(0.01 \sec^2 z)$ in the expression (18) for the refraction in seconds of arc, computed from (ℓ_0/r_0) without going through the numerical integration, then becomes $6''.6913$, whereas if we assume the mass-height to be equal to the pressure-height we get $6''.6710$.

(12) We may, therefore, exactly represent our normal conditions, and fairly accurately take account of variations of refraction because of variations of temperature, pressure, gravity, radius of curvature of the optical layers with latitude, vapor-pressure, etc., by using as a practical equation

$$R = \tan z \log_e n_0\; f\left\{[(2\,\ell_0/r_0 + k\,\ell_0^2/r_0^2) - \log_e n_0] \sec^2 z\right\} \qquad (21)$$

in which k, according to the approximation mentioned in the preceding paragraph, should be nearly 5, and $f(\ldots.)$ is to be obtained by using in equation (11) and its equivalents, instead of $(\sec^2 z)$, the argument of the function divided by 0.0023012464. This, equated to $(\sec^2 z)$, gives k equal to 4.9566.

(13) Tables 1 to 7, which follow, correspond to equation (21), which, with the results of the numerical integrations and with the adopted physical constants, constitutes the system of this paper.

Notation for Tables 1 to 13

Refractions from Equation (21)
$R = \tan z\,(\log_e n_0)\,f$
R = astronomical refraction
z = apparent zenith-distance of star
n_0 = index of refraction of local air
f = quantity from Table 6

B = reading of brass-scale barometer, mm
t_B = temperature of barometer, °C
$B_0 = B(1 - 0.0001625\, t_B)(1 - 0.002662 \cos 2\varphi) + \pi C$
$(n_0-1) = [(n-1) \text{ per } 1 \text{ mm}]\, B_0 / (1 + 0.003673\, t)$

φ = latitude
h = elevation, km
w = wave-length, microns in air
t = local air-temperature, °C
π = local vapor-pressure, mm
t' = wet-bulb temperature
C = quantity from Table 4

Table 1

w	(n - 1)	(n - 1) per one-mm pressure
		"
0.30	.00030706	.083337
0.40	.00029814	.080916
0.50	.00029419	.079842
0.60	.00029208	.079271
0.70	.00029083	.078931
0.80	.00029002	.078711
0.90	.00028947	.078561
1.00	.00028907	.078454

Table 4

w	C	w	C
0.30	-.1326	0.70	-.1586
0.40	-.1471	0.80	-.1598
0.50	-.1533	0.90	-.1607
0.60	-.1566	1.00	-.1613

Table 2

t	[1/(1 + 0.003673 t)]
°	
-35	1.147519
-30	1.123835
-25	1.101109
-20	1.079284
-15	1.058307
-10	1.038130
- 5	1.018708
0	1.000000
+ 5	0.981966
+10	0.964571
+15	0.947782
+20	0.931567
+25	0.915898
+30	0.900747
+35	0.886089
+40	0.871900
+45	0.858159

Table 3

(n_0-1)	$\log_e n_0$ minus (n_0-1)	(n_0-1)	$\log_e n_0$ minus (n_0-1)
"	"	"	"
0.0		55.8	
	.000		-.008
14.4		59.3	
	-.001		-.009
25.0		62.7	
	-.002		-.010
32.2		66.0	
	-.003		-.011
38.1		69.0	
	-.004		-.012
43.2		71.9	
	-.005		-.013
47.7		74.8	
	-.006		-.014
51.9		77.4	
	-.007		-.015
55.8		80.0	

(14) As an alternative to the repeated use of equation (21) in routine work, one may use a system of "Intermediate refractions" (similar in construction to Bessel's and the Pulkowa tables), the basic tables of which, from new computations to assure freedom from discontinuities, are presented as Tables 8 to 12 and parts of Tables 4 and 7. It is expected that a table of corrections to the intermediate refractions will be computed by the use of equation (21) for the particular observatory and for the range of physical conditions involved in the observations. It will probably be found that the table of corrections for any observatory will differ from that for the United States Naval Observatory, Washington, D. C., given as Table 12, by an amount which varies appreciably only with the zenith-distance (compare Table 13); this variation will be due principally to the variation of the radius of curvature of the Earth from place to place. More extensive tables of the system of intermediate refractions have been prepared for expeditious computing, giving (α + log tan z) for every minute of arc of zenith-distance and subdivided arguments of other quantities.

The Tables

(15) Table 1 gives, for temperature 0°C and for standard gravity (that of latitude 45°), for a number of wave-lengths, the refractive power (n - 1) of dry normal air, in radians, and the same in seconds of arc per 1 mm of pressure. The dry normal air is assumed to contain 0.0003 CO_2. The refractive power in seconds of arc at any temperature and pressure not too remote from normal values may be computed to be

$$(n - 1) = [(n - 1) \text{ per unit of B}]\; B/(1 + 0.003673\, t)$$

in which B is the barometer-reading and t is the temperature in degrees Centigrade.

The values of (n - 1) for 0° C and 760-mm pressure at standard gravity are computed from the following formula, in which w is the wave-length of light in microns in normal air, and B is the pressure in mm

$$(n - 1) \times 10^6 = [0.378167\, w^2/(w^2 - 0.005761)]\; [B/(1 + 0.003673\, t)] \qquad (22)$$

Table 5--$(2\ell_0/r_0 + k\ell_0^2/r_0^2) = (a + bt)$

(ℓ_0/r_0) for 0°C	a	b
	″	
.00124	+513.11	+1.8889
.00125	+517.26	+1.9042
.00126	+521.41	+1.9195
.00127	+525.56	+1.9348

(ℓ_0/r_0) for 0°C

On meridian

$(0.00125515 + 0.00000635 \cos 2\varphi)(1 - 0.000157\,h)$

On prime vertical

$(0.00125093 + 0.00000211 \cos 2\varphi)(1 - 0.000157\,h)$

On vertical circle making angle A with meridian

(meridian value) $\cos^2 A$ + (prime-vertical value) $\sin^2 A$

Table 6--Argument = $[(2\ell_0/r_0 + k\ell_0^2/r_0^2) - \log_e n_0]$ multiplied by $(0.001 \sec^2 z)$

Argument	f	Argument	f	Argument	f	Argument	f
″		″		″		″	
0	1.00000	18	0.96085	36	0.92845	54	0.90070
1	0.99759	19	0.95890	37	0.92680	55	0.89927
2	0.99522	20	0.95697	38	0.92516	56	0.89785
3	0.99287	21	0.95506	39	0.92354	57	0.89644
4	0.99055	22	0.95316	40	0.92193	58	0.89504
5	0.98827	23	0.95129	41	0.92034	59	0.89366
6	0.98601	24	0.94943	42	0.91876	60	0.89228
7	0.98378	25	0.94759	43	0.91718	61	0.89091
8	0.98157	26	0.94577	44	0.91563	62	0.88955
9	0.97939	27	0.94397	45	0.91408	63	0.88820
10	0.97724	28	0.94218	46	0.91255	64	0.88686
11	0.97511	29	0.94041	47	0.91103	65	0.88553
12	0.97301	30	0.93865	48	0.90952	66	0.88422
13	0.97093	31	0.93692	49	0.90802	67	0.88291
14	0.96887	32	0.93519	50	0.90654	68	0.88161
15	0.96683	33	0.93348	51	0.90506	69	0.88033
16	0.96482	34	0.93179	52	0.90360	70	0.87905
17	0.96282	35	0.93011	53	0.90215	71	0.87778
18	0.96085	36	0.92845	54	0.90070	72	0.87652

which was derived by the writer from the data given by Barrell and Sears [6] in publishing the results of their laboratory determination of the refractive indices of dry, CO_2-free air. The refractive power of dry air is considered to be proportional to its density over the range occurring in astronomical observations and is here assumed to be directly proportional to the pressure and inversely proportional to the quantity $(1 + 0.003673\,t)$, which is here adopted to represent the results of Chappuis, which are closely confirmed by Barrell and Sears. [See 1, p. 705 and 722, and 2, p. 226.]

The above formula resulted from the combination of the following formulas for the refractive powers of dry CO_2-free air and CO_2, respectively: For CO_2-free air

$$(n - 1) \times 10^6 = [0.378106\, w^2/(w^2 - 0.005761)]\, [B/(1 + 0.003673\, t)] \qquad (23)$$

For CO_2

$$(n - 1) \times 10^6 = [0.5820\, w^2/(w^2 - 0.006132)]\, [B/(1 + 0.00367\, t)] \qquad (24)$$

It is believed that this form for representing the refractive power, giving substantially the same residuals for the measures of Barrell and Sears, which were for wave-lengths 0.436 to 0.644 micron, is less likely to err in extrapolating than the Cauchy form, for which the higher terms are not negligible when a long range of wave-lengths is to be covered.

The local temperature and the local pressure are to be used. If the air inside the

Table 7--Correction for departure of local temperature from that of standard atmosphere, equations (12) and (13)

z	Correction to		z	Correction to	
	Refraction	$\log_{10}$ refr.		Refraction	$\log_{10}$ refr.
°	″		°	″	
70	-.0001Δt	.000000Δt	78	-.0024Δt	-.000004Δt
71	-.0002Δt	-.000001Δt	79	-.0036Δt	-.000005Δt
72	-.0003Δt	-.000001Δt	80	-.0054Δt	-.000007Δt
73	-.0004Δt	-.000001Δt	81	-.0083Δt	-.000010Δt
74	-.0006Δt	-.000001Δt	82	-.0139Δt	-.000015Δt
75	-.0009Δt	-.000002Δt	83	-.0242Δt	-.000024Δt
76	-.0012Δt	-.000002Δt	84	-.0458Δt	-.000039Δt
77	-.0017Δt	-.000003Δt	85	-.0961Δt	-.000071Δt

Table 8--Refractions using intermediate system

$$\log R = \log \tan z + \alpha + \beta + \gamma + (\lambda - 1)(\gamma + \beta/10) + \text{observatory correction}$$

z	α	$(\lambda - 1)$	z	α	$(\lambda - 1)$	z	α	$(\lambda - 1)$
° ′			° ′			° ′		
0 00	1.75825	.0013	70 50	1.75416	.0126	78 00	1.74768	.0297
5 00	1.75825	.0013	71 00	1.75409	.0129	78 10	1.74739	.0304
10 00	1.75824	.0013	71 10	1.75401	.0131	78 20	1.74708	.0312
15 00	1.75822	.0014	71 20	1.75393	.0133	78 30	1.74676	.0320
20 00	1.75819	.0015	71 30	1.75385	.0135	78 40	1.74643	.0329
25 00	1.75814	.0016	71 40	1.75376	.0137	78 50	1.74609	.0337
30 00	1.75808	.0018	71 50	1.75367	.0139	79 00	1.74573	.0346
35 00	1.75800	.0020	72 00	1.75358	.0141	79 10	1.74536	.0356
40 00	1.75790	.0023	72 10	1.75349	.0144	79 20	1.74497	.0366
41 00	1.75787	.0024	72 20	1.75340	.0146	79 30	1.74456	.0376
42 00	1.75784	.0025	72 30	1.75330	.0149	79 40	1.74413	.0386
43 00	1.75781	.0026	72 40	1.75320	.0152	79 50	1.74369	.0397
44 00	1.75778	.0026	72 50	1.75310	.0155	80 00	1.74323	.0408
45 00	1.75775	.0027	73 00	1.75300	.0158	80 10	1.74274	.0420
46 00	1.75771	.0028	73 10	1.75289	.0161	80 20	1.74223	.0433
47 00	1.75767	.0029	73 20	1.75278	.0164	80 30	1.74170	.0446
48 00	1.75763	.0030	73 30	1.75266	.0167	80 40	1.74114	.0460
49 00	1.75759	.0031	73 40	1.75255	.0170	80 50	1.74055	.0473
50 00	1.75754	.0032	73 50	1.75243	.0173	81 00	1.73993	.0488
51 00	1.75749	.0034	74 00	1.75230	.0177	81 10	1.73928	.0504
52 00	1.75743	.0036	74 10	1.75217	.0180	81 20	1.73860	.0520
53 00	1.75737	.0038	74 20	1.75204	.0184	81 30	1.73788	.0537
54 00	1.75730	.0040	74 30	1.75190	.0187	81 40	1.73712	.0554
55 00	1.75723	.0042	74 40	1.75176	.0191	81 50	1.73633	.0573
56 00	1.75715	.0044	74 50	1.75161	.0195	82 00	1.73549	.0592
57 00	1.75706	.0046	75 00	1.75146	.0199	82 10	1.73460	.0613
58 00	1.75697	.0049	75 10	1.75131	.0203	82 20	1.73366	.0635
59 00	1.75686	.0052	75 20	1.75115	.0207	82 30	1.73267	.0657
60 00	1.75675	.0055	75 30	1.75099	.0211	82 40	1.73161	.0680
61 00	1.75662	.0059	75 40	1.75082	.0216	82 50	1.73050	.0705
62 00	1.75648	.0063	75 50	1.75064	.0220	83 00	1.72931	.0732
63 00	1.75633	.0067	76 00	1.75046	.0225	83 10	1.72805	.0760
64 00	1.75616	.0072	76 10	1.75027	.0230	83 20	1.72672	.0788
65 00	1.75596	.0077	76 20	1.75007	.0235	83 30	1.72529	.0819
66 00	1.75574	.0083	76 30	1.74987	.0240	83 40	1.72377	.0851
67 00	1.75549	.0090	76 40	1.74966	.0246	83 50	1.72215	.0885
68 00	1.75521	.0098	76 50	1.74944	.0251	84 00	1.72041	.0921
69 00	1.75489	.0106	77 00	1.74922	.0257	84 10	1.71856	.0959
70 00	1.75452	.0117	77 10	1.74898	.0263	84 20	1.71657	.0999
70 10	1.75445	.0118	77 20	1.74874	.0270	84 30	1.71443	.1041
70 20	1.75438	.0120	77 30	1.74849	.0276	84 40	1.71213	.1086
70 30	1.75431	.0122	77 40	1.74823	.0283	84 50	1.70966	.1132
70 40	1.75424	.0124	77 50	1.74796	.0290	85 00	1.70700	.1179

Table 9--$B' = B + \pi C$ (C from Table 4)

$\beta = \beta_o + \Delta\beta_t + \Delta\beta_w$ (from Tables 9-11)

B'	β_o	B'	β_o	B'	β_o	B'	β_o	B'	β_o	B'	β_o
mm		mm		mm		mm		mm		mm	
710	-.02380	724	-.01532	738	-.00700	752	+.00116	766	+.00917	780	+.01703
711	-.02319	725	-.01472	739	-.00642	753	+.00173	767	+.00973	781	+.01759
712	-.02258	726	-.01412	740	-.00583	754	+.00231	768	+.01030	782	+.01815
713	-.02197	727	-.01353	741	-.00524	755	+.00289	769	+.01086	783	+.01870
714	-.02136	728	-.01293	742	-.00466	756	+.00346	770	+.01143	784	+.01925
715	-.02076	729	-.01233	743	-.00407	757	+.00403	771	+.01199	785	+.01981
716	-.02015	730	-.01174	744	-.00349	758	+.00461	772	+.01256	786	+.02036
717	-.01954	731	-.01114	745	-.00290	759	+.00518	773	+.01312	787	+.02091
718	-.01894	732	-.01055	746	-.00232	760	+.00575	774	+.01368	788	+.02146
719	-.01833	733	-.00996	747	-.00174	761	+.00632	775	+.01424	789	+.02202
720	-.01773	734	-.00937	748	-.00116	762	+.00689	776	+.01480	790	+.02257
721	-.01713	735	-.00877	749	-.00058	763	+.00746	777	+.01536		
722	-.01652	736	-.00818	750	.00000	764	+.00803	778	+.01592		
723	-.01592	737	-.00759	751	+.00058	765	+.00860	779	+.01648		

Table 10

t_B	$\Delta\beta_t$	....	t_B	$\Delta\beta_t$	....	t_B	$\Delta\beta_t$	....
t	....	γ	t	....	γ	t	....	γ
°C			°C			°C		
-30	+.00211	+.06637	- 5	+.00035	+.02372	+20	-.00141	-.01512
-29	+.00204	+.06458	- 4	+.00028	+.02209	+21	-.00148	-.01660
-28	+.00197	+.06280	- 3	+.00021	+.02048	+22	-.00156	-.01808
-27	+.00190	+.06102	- 2	+.00014	+.01887	+23	-.00163	-.01956
-26	+.00183	+.05926	- 1	+.00007	+.01726	+24	-.00170	-.02102
-25	+.00176	+.05750	0	.00000	+.01567	+25	-.00177	-.02249
-24	+.00169	+.05574	+ 1	-.00007	+.01407	+26	-.00184	-.02395
-23	+.00162	+.05400	+ 2	-.00014	+.01249	+27	-.00191	-.02540
-22	+.00155	+.05226	+ 3	-.00021	+.01091	+28	-.00198	-.02685
-21	+.00148	+.05053	+ 4	-.00028	+.00933	+29	-.00205	-.02829
-20	+.00141	+.04880	+ 5	-.00035	+.00776	+30	-.00212	-.02973
-19	+.00134	+.04708	+ 6	-.00042	+.00620	+31	-.00219	-.03117
-18	+.00127	+.04537	+ 7	-.00049	+.00464	+32	-.00226	-.03260
-17	+.00120	+.04367	+ 8	-.00057	+.00309	+33	-.00234	-.03402
-16	+.00113	+.04197	+ 9	-.00064	+.00154	+34	-.00241	-.03544
-15	+.00106	+.04028	+10	-.00071	.00000	+35	-.00248	-.03686
-14	+.00099	+.03859	+11	-.00078	-.00154	+36	-.00255	-.03827
-13	+.00092	+.03691	+12	-.00085	-.00307	+37	-.00262	-.03967
-12	+.00085	+.03524	+13	-.00092	-.00459	+38	-.00269	-.04108
-11	+.00078	+.03358	+14	-.00099	-.00611	+39	-.00276	-.04247
-10	+.00071	+.03192	+15	-.00106	-.00763	+40	-.00283	-.04387
- 9	+.00063	+.03026	+16	-.00113	-.00914	+41	-.00290	-.04526
- 8	+.00056	+.02862	+17	-.00120	-.01064	+42	-.00298	-.04664
- 7	+.00049	+.02698	+18	-.00127	-.01214	+43	-.00305	-.04802
- 6	+.00042	+.02534	+19	-.00134	-.01363	+44	-.00312	-.04940

telescope is assumed to be homogeneous, these are temperature and pressure of the air immediately in front of the object glass of the telescope. It is desirable that the effective wave-length for the particular observer, spectral type of star, zenith-distance, etc., should be determined as by the special or general use of a coarse diffraction-grating in front of the objective of the telescope.

The writer believes that direct measures in the laboratory of the refractive power of air furnish a more accurate value of the coefficient of tan z for the correction of astronomical work than can be derived from comparisons of circumpolar-star observations. If thermometers and barometers are standardized, the comparisons of circumpolar observations of star zenith-distances may yield other valuable results, such as flexure-coefficients, or the coefficient with which the mean atmospheric mass-gradient for observing weather modifies the refraction. The latter varia-

Table 11

w	$\Delta\beta_w$
0.30	+.02117
0.35	+.01336
0.40	+.00836
0.45	+.00497
0.50	+.00256
0.55	+.00079
0.60	-.00056
0.65	-.00160
0.70	-.00243
0.75	-.00309
0.80	-.00364
0.85	-.00409
0.90	-.00446
0.95	-.00478
1.00	-.00506

Table 12--Observatory correction for Washington meridian

z	B = 750 mm for t			t = 10°C for	
	-20°C	+10°C	+40°C	720 mm	780 mm
°	In units of fifth decimal of log R				
0	0	0	0	0	0
40	0	0	- 1	0	0
60	-1	0	- 1	0	0
70	-2	0	- 2	0	0
76	-4	0	- 5	0	0
80	-6	0	- 7	+1	0
83	-9	0	-10	+1	0
85	-8	0	-11	+1	0

Table 13--Pulkowa minus Washington meridian

z	Value
°	
0	+.00082
40	+.00082
60	+.00082
70	+.00083
76	+.00085
80	+.00087
83	+.00092
85	+.00099

tion of refraction would be about proportional to the square of the secant of the zenith-distance, not proportional to the tangent of the zenith-distance.

(16) Table 2 gives the reciprocal of (1 + 0.003673 t).

(17) Table 3 gives the reduction from (n - 1) to $\log_e n_0$ in seconds of arc.

(18) Table 4 gives the change in barometric pressure which is equivalent to the correction of refractive power because of water-vapor content of the air. The values are based on formula (25) for the refractive power of water-vapor, deduced by the writer to represent the observations of Barrell and Sears [2, p. 155; 3, p. 235; 6].

$$(n - 1) \times 10^6 = [0.3162\ w^2/(w^2 - 0.0088)]\ [B/(1 + 0.00367\ t)] \tag{25}$$

(19) Correction for the temperature of the barometer--Correction of (n - 1) equivalent to correction of barometer for mercury and brass-scale temperature may be accomplished by multiplying by (1 - 0.0001625 t_B), in which t_B is the temperature of the barometer in °C; or by [1 - 0.0000903 (t_B - 28.5)] in which t_B is the temperature in °F of a barometer graduated on the English system. [See 2, p. 117.]

(20) Correction for the local value of gravity--Correction of (n - 1) because of variation of gravity with latitude and with elevation on land may be accomplished by multiplying by (1 - 0.002662 cos 2φ) (1 - 0.0001963 h), φ being the latitude and h the elevation in km.

If a gravity-determination has been made for the station, this may be used to derive a more accurate correction than that given by the above factor.

No table has been given for this correction because it is necessary to compute it only once for each station. [See 2, p. 104.]

(21) Table 5 gives formulas and auxiliary quantities for obtaining $(2\,\ell_0/r_0 + k\,\ell_0^2/r_0^2)$ in seconds of arc, which, for a particular observatory, is a function of the temperature. The values here given result from: Density of mercury at 0° C, 13.59545; density of air at 760-mm pressure at standard gravity, for Centigrade temperatures, [0.0012928/(1 + 0.003670 t)]; dimensions of the Earth, those given in the American Ephemeris and Nautical Almanac for 1935, p. xvi. [References: 2, pp. 91, 97; 3, pp. 176, 169; 4, p. xvi.]

(22) Table 6 gives the function f of equation (21), tabulated with the argument $[(2\,\ell_0/r_0 + k\,\ell_0^2/r_0^2) - (\log_e n_0)]\ (0.001 \sec^2 z)$ in seconds of arc. ($\sec^2 z$) may be derived from the tangent, using the equation $\sec^2 z = 1 + \tan^2 z$.

(23) Table 7 enables corrections to be made for diurnal or other departures, in the lowest part of the atmosphere, of temperature from the temperature of the adopted atmosphere of equations (12) and (13), if such departures can be measured or estimated. The local temperature is assumed to exist in a thin layer, the ray, traced backward from the observer, entering the

adopted atmosphere with a changed zenith-distance. It is notable that these corrections are not proportional to the tangent of the zenith-distance, but are about proportional to the fourth power of the secant of the zenith-distance. Another kind of variation from the adopted atmosphere is that of the local temperature from the temperature, at the same elevation, of a point below the mean position at which refraction takes place, of the order of eight km times tan z away from the observer in a horizontal direction.

The quantities in Table 7 serve also by indicating the relative reliability of the computed values of refraction for various zenith-distances, the departures of local temperature from the corresponding temperature of the adopted atmosphere being of the order of 5° C.

(24) Room-refraction, and similar refractions--For room-refraction and for refraction in the telescope-tube we may use the equation

$$d \text{ refraction} = (d\, s)(d \log_e n)/(d\, P) \tag{26}$$

in which s is distance along the ray, n is the index of refraction, and P is distance perpendicular to the ray. Differential thermometers of the electrical-resistance type may be useful in investigating local variations of density, which, since the pressure is due to weight of the air above a point, can be completely determined by the measurement of temperatures or variations of temperature.

(25) Tables 8 to 11, along with parts of Tables 4 and 7, constitute a system of intermediate refractions, which, for a particular observatory, requires, as illustrated by Tables 12 and 13, small corrections which may be computed by the use of equation (21) and Tables 1 to 7 and a comparison with corresponding computed values of intermediate refractions. Using Tables 8 to 12

$$\log_{10} R = \log_{10} \tan z + \alpha + \beta + \gamma + (\lambda - 1)(\gamma + \beta/10) + \text{Table like 12} \tag{27}$$

(26) References--

[1] W. F. Meggers and C. G. Peters, Measurements on the index of refraction of air for wavelengths of light from 2218 Å to 9000 Å, Sci. Papers U. S. Bur. Stand., No. 327, 1918.
[2] Smithsonian physical tables, fifth revised ed., 1910.
[3] Smithsonian physical tables, eighth revised ed., 1934.
[4] American Ephemeris and Nautical Almanac for 1935.
[5] W. J. Humphreys, Physics of the air, third ed., 1940.
[6] H. Barrell and J. E. Sears, Refraction and dispersion of air in the visible spectrum, Trans. R. Soc. London, v. 238, pp. 1-14, 1939.

Comparison with Washington circumpolar observations and the used Pulkowa refraction-system

(27) The Pulkowa refraction-system used in the reduction of the United States Naval Observatory observations since about 1900 is published in Publications of the United States Naval Observatory [Second Ser., v. 4, Appendix II, 1904]. The corrections to that system indicated by the Washington circumpolar observations since 1900, published as indicated, are as given in Table C.

The correction indicated by the system of this paper averaged over the approximate range of Washington mean observing temperatures, 0° C to 24°4 C (32° F to 76° F), for 60 per cent relative humidity, is -0.106. This is about the amount corresponding to the difference of gravity

Table C--Corrections to Pulkowa refraction-system from observations at Washington

Instrument	Years	Corr. to coeff. of tan z	U.S.N.O. Pub.
9-inch transit-circle	1903-11	-".134 ±".026	V.9, Pt.1, p.Acxxx
	1918-24	-.065	V.13, p.54
6-inch transit-circle	1911-18	-.055 ±.013	V.11, p.90
	1925-30	-.163 ±.036	V.14, Pt.1, p.9
5-inch altazimuth	1916-33	+.03 ±.10 (about)	V.14, p.138
Simple mean, transit-circles		-.104	

Table D--Indicated further corrections to the used Pulkowa refractions

(Units of the fifth decimal of log R)

z	t in °C						Averaged for temperatures 0° to 24°.4 C	Washington mid-summer minus mid-winter
	-20	-10	0	+10	+20	+30		
0°	+50	+49	+39	+16	-25	-100	0	-90
45	+47	+47	+37	+15	-25	-100	-1	-88
60	+49	+50	+40	+17	-24	- 99	+1	-90
70	+51	+50	+41	+18	-23	- 99	+2	-90
75	+45	+47	+38	+15	-26	-102	-1	-90
80	+35	+39	+33	+13	-27	-102	-3	-86
83	+25	+33	+31	+13	-25	-100	-2	-82
85	+ 4	+19	+22	+11	-22	- 89	-2	-67

at the two observatories (compare Table 13, which shows also the effect of the difference of the curvature of the Earth at the two observatories).

(28) The system of this paper, when wave-length 0.578 micron and 60 per cent relative humidity are assumed and when data for Washington are used, indicates that the corrections given in Table D (maximum 1".19) are necessary when using the Pulkowa refraction-system of Volume 4, Appendix II [Pub. U. S. Naval Observ., Second Ser.] with the log R diminished by 0.00081, which corresponds to the gravity-correction of about -0".107 tan z.

These corrections are due mainly to the lack of facilities for correction for individual values of vapor-pressure in the Pulkowa refraction-system of 1870. The 1930 edition of the Pulkowa Refraction Tables include facilities for such corrections which are in substantial agreement with the system of this paper. The first of the series of observations listed in Table C is the only one of the series for which individual observations are published; from 149 observations of Polaris in that series, the value derived for the apparent change of declination, relative to the Pulkowa refraction-system used, between mid-winter and mid-summer is 0".145 ± 0".042; the value derived from the system of this paper, assuming 60 per cent relative humidity, is 0".144 in the same direction.

Table D also shows, when considered with or without the quantities given in Table 13, that there is no notable disagreement in the variation of refraction with zenith-distance between the Pulkowa system as it has been used for the cited observations and the system of this paper.

Gaithersburg, Maryland

THE READJUSTMENT OF THE FIRST-ORDER LEVELING IN THE ALLUVIAL VALLEY OF THE MISSISSIPPI RIVER

Charles J. Clifford

The first leveling of first-order accuracy in the Alluvial Valley of the Mississippi was run in 1876 and 1877 when the Corps of Engineers leveled from Cairo, Illinois, to Columbus, Kentucky, and from Memphis, Tennessee, to Friar Point, Mississippi. Between 1879 and 1881 the United States Coast and Geodetic Survey ran a line from New Orleans, Louisiana, to Greenville, Mississippi, where the work was taken up by the Corps of Engineers and continued to Arkansas City, Arkansas. Leveling proceeded at a steady rate, until by 1906 the Alluvial Valley was covered by a network of lines, and the original lines along the river had been rerun.

Since the time of de Soto, Joliet, Marquette, and de la Salle, the Mississippi has shown scant respect for the works of man--and level-lines have been no exception. A great many bench-marks were undermined and caved into the river, and others settled because of unstable ground-conditions, especially in the lower reaches of the river. The resulting gaps and unreliable elevations have made it necessary from time to time to execute a considerable amount of releveling. Beginning in 1929 and continuing through 1940, most of the first-order level-lines in the Alluvial Valley south of an east-and-west line through Friar Point, Mississippi, have been rerun by the Second New Orleans Engineer District, the Vicksburg Engineer District, and the United States Coast and Geodetic Survey.

All this new leveling, with the resulting new elevations for old marks, would have been a sufficient reason for readjustment. But there were other considerations that made a readjustment desirable. When the Corps of Engineers started their first leveling at Cairo and at Memphis, there were no connections with sea-level and therefore datum-planes were assumed. Later a connection was made to a single tide-station on the Gulf of Mexico at Biloxi, Mississippi. The datum resulting from this connection was called mean Gulf level. Thus there were three datum-planes in use along the Mississippi; mean Gulf level; Memphis datum, which was 6.630 feet below mean Gulf level; and Cairo datum, 20.434 feet below mean Gulf level. After the final determination of mean Gulf level, the use of Memphis datum and Cairo datum was discontinued. The Coast and Geodetic Survey introduced a fourth set of elevations by including the Engineers' leveling in the adjustment of the control-net of the United States, adding several other connections to tide-stations on the Atlantic, Gulf, and Pacific coasts, besides the one at Biloxi determined by the Engineers. It was easy enough to convert elevations on the Memphis and the Cairo datum-planes to mean Gulf-level elevations by applying the necessary corrections. However, it was not possible to apply a single correction in order to convert Coast Survey elevations to mean Gulf level elevations, except in the vicinity of Biloxi. In order to secure a single reference-plane and to place all their elevations on the mean-sea-level datum, the Mississippi River Commission requested the United States Coast and Geodetic Survey to adjust the recent leveling to the Sea Level Datum of 1929. This is the datum resulting from the 1929 General Adjustment, in which sea-level was held fixed as determined at 26 tide-stations, 21 in the United States and five in Canada.

From Cape Girardeau, Missouri, the Mississippi flows southward through an enormous flood-plain that ends in the vicinity of Baton Rouge. Below that point a huge delta has been built into the Gulf of Mexico. The Alluvial Valley is popularly understood to include both the true flood-plain and the delta. The adjustment included about three-fourths of the length of the Alluvial Valley, but it extended a considerable distance east and west of its limits. The area involved covered all of Mississippi and Louisiana, and about one-fourth of Arkansas, with small parts of Tennessee and Alabama.

Usually the most time-consuming part of a level-adjustment is the preliminary study that must be made in order to choose the junction bench-marks where two or more lines join. But on this project it was first necessary to complete the computation of the observed elevations along the Engineers' lines from the differences in elevation that were furnished, and to compute the orthometric corrections. After all of the computations were completed, the junction studies were begun. The first step is to draw sketches, which we call junction details, showing the relationship between the various lines, and the bench-marks that were included in them. These sketches are made with colored pencils, each color representing a specific line.

The junction details vary from those showing connections to one or two marks, to those involving as many as 30 circuits. Of course, it is easy to choose a junction mark when only one or two marks are used. But when the detail becomes more complicated it is often necessary to make local adjustments in order to secure consistent differences in elevation between the local bench-marks. When these adjustments are made, the marks at the extremities are used as the junctions and the differences between them are held fixed as determined by the detailed adjustment.

In the Alluvial Valley adjustment 93 level-lines were used, and 82 junction details were made, although only 72 of the junctions were actually used. The extra studies were made in case it proved necessary to extend the adjustment beyond the limits originally planned. There were 16 local adjustments involving 103 equations.

In order to reduce the affected area to a minimum, it was desirable to select the fixed junctions so as to hold previously adjusted elevations as close as possible to the new work to be adjusted. The purpose of this was to cause the least change in elevations along old lines that had not been releveled. The fixed junctions were chosen at Corinth, Mississippi; Memphis, Tennessee; Friar Point, Mississippi; Little Rock and Huttig, Arkansas; Shreveport, Keithville, South Mansfield, Iowa Junction, and Lafayette, Louisiana; Biloxi, Mississippi; and Mobile and York, Alabama. This first choice was also the last, since the closures of the outer ring of circuits were very good.

When the circuit-closures were computed, it was found necessary to reject one short link involving a river crossing, thus combining two bad closures into one good one. The adjustment then contained 53 circuits composed of 147 links. There were two large circuit-closures amounting to 117.1 mm in 636 km and 117.0 mm in 404 km. While these closures are somewhat larger than than the allowable limit for first-order leveling, the corrections to the various links were not excessive. The smallest closure was 1.0 mm in 215 km. The largest correction resulting from the adjustment was 45.8 mm in 118 km, while the smallest was zero in 40 km. The average rate of distribution of closure was slightly less than 0.2 mm per km. This was computed by taking the sum of the v's without regard to sign, and dividing by the sum of the line lengths.

It was possible to compare the resulting elevations of 40 junctions with elevations previously determined. There were 15 elevations that were from 14 to 82 mm higher than the old ones; while 23 were from 17 to 88 mm lower, with two 144 and 199 mm lower. The last two values probably indicate settlement of the marks, since they are so much greater than those nearby. With a few exceptions, the positive values are near the outer edges of the net, while the negative ones are mostly in the vicinity of the river.

The Alluvial Valley Adjustment accomplished two desirable results. It permitted the fitting of a large amount of new leveling to the level-net of the United States, and, what is more important, it placed the work of the Corps of Engineers on the Sea Level Datum of 1929, so that for the first time all of the first-order leveling in the area is on a common datum-plane.

U. S. Coast and Geodetic Survey,
Washington, D. C.

ORGANIZATION OF GEODETIC AND PRECISE DATA FOR NATIONAL DEFENSE

William F. Barck

The plan to assemble geodetic and precise control-data for general military use embraces the United States and possessions, Mexico, Central and South America, and islands of strategic importance for Hemisphere Defense. All the data for first-, second-, and third-order triangulation, traverse, and leveling will be arranged in pamphlet or bulletin form. Each unit will contain all the control available in an area covered by a United States Geological Survey 15-minute quadrangle sheet. The area of the United States will require about 13,000 of these quadrangle sheets. Certain areas, involving about 28 States, have been given first priority and will require control-information to cover about 3,000 quadrangles.

The positions, descriptions, and other horizontal control-data, and the leveling descriptions and elevations, now available in many forms, will be reduced to a manuscript arrangement suitable for military use. The positions will be based on the North American Datum of 1927 and the elevations on standard Mean Sea-Level 1929. A suitable density of points will be obtained where possible. The quadrangle areas will be segregated by States and the finished material will be placed on file in the Corps Area Engineer Offices at the nine Corps Area Headquarters. Geographic coordinates and State plane-coordinates on the standard projections will be converted into military-grid coordinates on the polyconic projection and military-grid azimuths will be made available. A graphic diagram will be provided for all control within each 15-minute quadrangle bulletin and each bulletin containing a diagram will be indexed geographically, that is, designated by latitude and longitude of the southeast corner of the quadrangle.

All available United States Coast and Geodetic Survey data in the United States have been forwarded to the nine Corps Area Engineer Offices, the United States Geological Survey control-data will be forwarded to all the Corps Areas during May, 1941, and the United States Engineer Department has started to prepare information on their control as employed in the 47 Engineer Districts in the United States. Information from other Federal agencies, such as the Soil Conservation Service, Soil Survey Division, Forest Service, and the Hydrographic Office, is being assembled and will be forwarded to the Corps Areas. State geodetic and cadastral-survey units, public-works departments, planning commissions, etc., are being called upon to furnish existing geodetic or precise control-data.

Six Work Projects Administration projects have been organized to date to process the material forwarded to the Corps Areas and, when required, other Work Projects Administration units will be sparked to complete this servicing job in a suitable form for all the War Department uses. This plan will enable the Corps Area Engineers:

To make immediate distribution to Topographic Engineering Bureaus and Artillery Units for adequate control for the starting of field-operations by these units.
To assist the mapping agencies to lay controlled mosaics with a minimum of field-work.
To facilitate employment of photogrammetric processes in areas which are densely ground-controlled.

To avoid delays in obtaining information of existing control-data and to overcome the constant repetition in furnishing these data by the establishing agency.

The job just outlined, the assembly in nine places in the United States of the results of all control-surveys from many different producing agencies, in many different forms and coming from all parts of the United States, is a man-size "chore." The Congress in the early 20's framed some legislation calling for about 120 million dollars to be expended over a period of about 15 or 20 years to complete the necessary control and topographic surveys to produce a set of maps covering the entire area of the United States, but so far the job has not been completed because of inadequate appropriations.

You will recall that the War Department plan calls for the reduction of the many forms of control-data to some "common denominator." The material as found at present is arranged in arcs, lines, quadrangles, counties, States, and projects, alphabetically and geographically.

The descriptions of triangulation-stations or bench-marks contain primary references to towns, section-corners, and local landmarks, etc., and may be found in separate tabulations or with the corresponding positions and elevations. The final results are issued by lithography, mimeograph, photostat, or typewritten sheets. In order to obtain a copy of the material the following problems arise: What are the addresses of the various sources of information; what is the availability of copies of material, including indices and diagrams; how much time and cost are necessary to reproduce this material, etc.

In this connection, I want to mention a microfilming job we tried with the cooperation of the United States Geological Survey. About 225,000 original data-sheets are on file with the Geological Survey. This information (triangulation and traverse-control of third-order accuracy) consisted of material in published form (out of print), typewritten and photostatic sheets, etc. Since this material represented the only copy available and was in constant demand for reference to answer the normal requests made on the Geological Survey, it could not be removed from the control-section of the Geological Survey. By the use of microfilming, film negatives and photo positives were made for distribution and a uniform arrangement of material by quadrangles was obtained. All the horizontal and vertical control-data were assembled in quadrangles of one degree of latitude and one degree of longitude. An index accompanies each degree quadrangle which shows what kind of control is available in each 15-minute quadrangle. The material is arranged so that it is available for purposes of reproduction. This project was serviced by a local Work Projects Administration unit and supervision was provided by the United States Geological Survey. I believe this job, if handled by typewriter with adequate proof-reading, would have taken at least two months longer and the cost probably would have been about 2-1/2 times greater than the microfilm job.

With reference to the condition of material found, such as the accuracy (actual or claimed) and the status of first-, second-, and third-order work as to whether the data are adjusted, unadjusted, preliminary, etc., and the datum used, all these questions indicate that additional work is necessary to bring all material of record up to present-day standards.

In conclusion, I would like to leave with you some thoughts that have come to me in connection with this problem:

From the point of view of the "consumer," how can the products of the control-survey organizations ("producers") be harmonized, coordinated, standardized, etc., for easy accessibility and distribution?

How can unnecessary duplication best be avoided?

Can results be standardized in such a way that each producer will use nearly the same form in tabulating data and then maintain similar files so that they may exchange information with one another that would be immediately absorbed in the files without rearrangement or recopying? It is respectfully suggested that this matter is a challenge to geodesists to improve the situation in the interest of national efficiency.

Finally, I wish to express my real appreciation for the fine cooperation shown to me and my associates of the War Department by all the agencies mentioned above, particularly those in Washington, D. C.

Corps of Engineers,
U. S. War Department,
Washington, D. C.

RECENT PROGRESS IN GEODETIC SURVEYS OF THE UNITED STATES COAST AND GEODETIC SURVEY

H. W. Hemple

During the past year, the United States Coast and Geodetic Survey has had in continuous operation two triangulation-parties in the mountains of the far Western States, one triangulation-party operating in the Middle Western States, and one triangulation-party operating in the Eastern States. All of these parties are double units observing at night on signal-lamps using first-order direction theodolites. Those in the Middle West and East are using the portable steel triangulation-tower.

The triangulation-parties operating in the Western States consist of about 26 men equipped for strenuous physical work in mountain regions. During the past year one party has completed observations on an arc of triangulation along parallel of latitude 47° 30' from Seattle, Washington, to Great Falls, Montana, a distance of about 450 miles (Fig. 1). Numerous Forest Service lookout-towers were located on this arc. Connections were also made to the surveys in the Grand Coulee Dam Region. Later this party operated in the Willamette Valley Region of Oregon from Eugene north to Portland. This latter arc was requested by the Corps of Engineers, Portland District, to coordinate detached surveys. This party also extended the triangulation in Oregon from Portland to the Coast in the vicinity of Tillamook to strengthen the coastal net in this vicinity. The party is now operating in Humboldt Bay, California, measuring a base-line and extending an overall net over this region in order to coordinate various detached surveys of the Corps of Engineers. Preparations are now under way to transfer this unit to Alaska to extend an arc of triangulation along the Richardson Highway from Valdez to Fairbanks, and thence along the Alaskan Railroad to Broad Pass where a connection will be made to existing control extending north from Anchorage. The Alaskan survey is being done at the request of the Corps of Engineers.

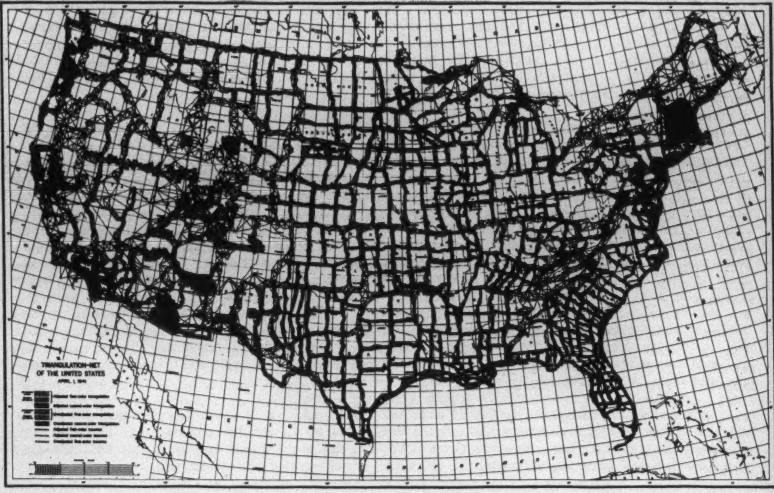

Fig. 1--Triangulation-net of United States, April 1, 1941

A second party operating in the Western States provided a triangulation-connection from surveys in the vicinity of Sacramento, California, eastward to existing control in the vicinity of Lake Tahoe. Later an arc was run in Nevada along parallel of latitude 41° 00' north from the California-Nevada Boundary eastward to Salt Lake City, Utah, a distance of about 420 miles. This party then transferred to southern California to extend control from Palmdale westward to the vicinity of Santa Barbara. Much rainy weather during January, February, and March, 1941, prevented effective work, and the party was transferred to El Centro, California. The control in the vicinity of Santa Barbara, California, will be done this spring. The work in the vicinity of El Centro consists of repeat-observations on the arcs centering at this point to detect the earth-movements due to the earthquake of May 18, 1940. The arc from Yuma, Arizona, to Jacumba, California, along the United States-Mexican Boundary and the arc from the boundary to Niland, California, were originally observed over in 1935. Additional arcs east and west of El Centro were also accomplished in 1938. These arcs are now being reobserved, and the resulting data will give us information as to the extent of the earth-movement due to seismological activities.

The steel-tower triangulation-party operating in the Middle Western States consists of about 38 men. This party completed the triangulation along the Arkansas River to the vicinity of Muskogee, Oklahoma, requested by the Army Engineers to coordinate surveys for flood-control purposes. The party then moved to the Upper Peninsula of Michigan and completed the arc from Rhinelander, Wisconsin, to Rockland, Michigan. The completion of this arc permits the adjustment of the control-net in this region.

The triangulation along parallel of latitude 42° 35' north from the vicinity of Ford Dodge, Iowa, to Butte, Nebraska, a distance of 210 miles, was also completed. The arc along parallel of latitude 37° 30' north from Wichita, Kansas, eastward to the vicinity of Fort Scott, Kansas, and the arc in Arkansas along latitude 36° 20' north between longitudes 93° west and 94° west was also accomplished. This party has also completed the arc along the 93rd meridian from Hot Springs, Arkansas, southward to Lake Charles, Louisiana, a distance of over 310 miles. The party is now extending the triangulation along meridian 92° 00' west from Opelousas, Louisiana, northward to Monroe, Louisiana. This region in Louisiana is of particular importance at the present time because of the army maneuvers held here last year and also scheduled for this year.

The party operating in the Eastern States also consists of about 38 men. The work done by this party consists of an arc in New York along the 42nd parallel from the Hudson River westward to Elmira and an arc along the 75th meridian from Port Jervis, New York, to Utica, New York. The party also measured a base-line in the vicinity of Baltimore, Maryland, and made connections therefrom to the city-control scheme. Later this party provided the triangulation on the arc along the Alabama-Georgia boundary-line from Opelika, Alabama, northward to Anniston, Alabama, with cross arcs from Roanoke, Alabama, to Atlanta, Georgia, and from Roanoke, Alabama, to Rockford, Alabama, and an arc north and south through Newnan, Georgia, from Columbus, Georgia, to the 34th parallel.

Three triple-unit leveling parties consisting of about 20 men each have been in operation (Fig. 2). One party has worked in the Sequoia National Park in southern California, and in Nevada south of Carson City. This party is now leveling a line along the Pacific Coast from Crescent City, California, to Astoria, Oregon, and thence to Portland, Oregon. Frequent connections are being made to tidal bench-marks established in harbors along the Coast. Also several lines are being run eastward to connect to the first-order level-lines in the interior valley.

Another party has rerun several lines in Colorado and New Mexico necessary so that the adjustments of the net in these regions may be completed. This party at the request of the Army Engineers also provided a first-order level-line in the Arkansas River Valley to coordinate Corps of Engineers leveling along this river. During the past several months this party has been rerunning the leveling net in the vicinity of Boulder City, Nevada. The original leveling in this region was done in 1935, with the purpose in mind that after the building of Boulder Dam and the consequent filling in of Lake Mead these lines would be releveled to determine any possible settlement due to this added load. Certain of these lines are now under water for comparatively short stretches, and it was necessary to install four automatic water-gages along the shores of Lake Mead in order to carry the level-line across the Lake. The results obtained by this leveling party are now being studied and analyzed.

The third level-party has operated in various States of the Middle West, South, and East, including Minnesota, North Dakota, South Dakota, Michigan, Missouri, Kentucky, Alabama, West Virginia, and Virginia. The purpose of this leveling was to permit the adjustment of level-nets in these States. In Virginia also area-leveling has been carried on in certain regions, particularly in the vicinity of Fairfax, Warrenton, Newton, and Garrisonville.

The only astronomical work done during the past year has been a few scattering azimuths. These include four azimuths of Laplace accuracy (average probable error slightly less than 0".3) in Arkansas, Louisiana, Nevada, and New York and three of third-order accuracy (average probable error about 0".9) in the West Indies.

A gravity-party has been working in the Central and East-Central States since last August

(Fig. 3). The purpose of this work has been to improve the general distribution in this area of basic gravity-stations. Work was done in the following States: Virginia, Ohio, Illinois, Indiana, Michigan, Wisconsin, Minnesota, North Dakota, Missouri, Arkansas, Mississippi, Louisiana, and Alabama. A number of the stations in North Dakota were determined at the request and with the cooperation of the State geologist.

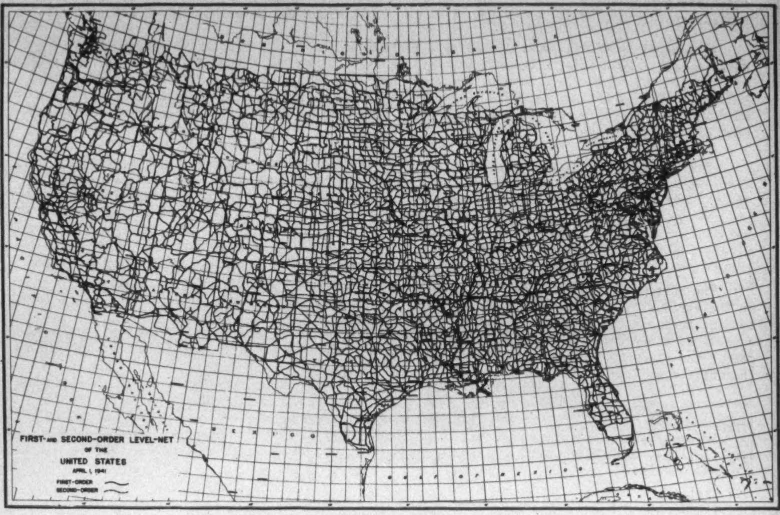
FIRST- AND SECOND-ORDER LEVEL-NET
OF THE
UNITED STATES
APRIL 1, 1941
FIRST-ORDER
SECOND-ORDER
MEXICO
GULF OF MEXICO

Fig. 2--Level-net of United States, April 1, 1941

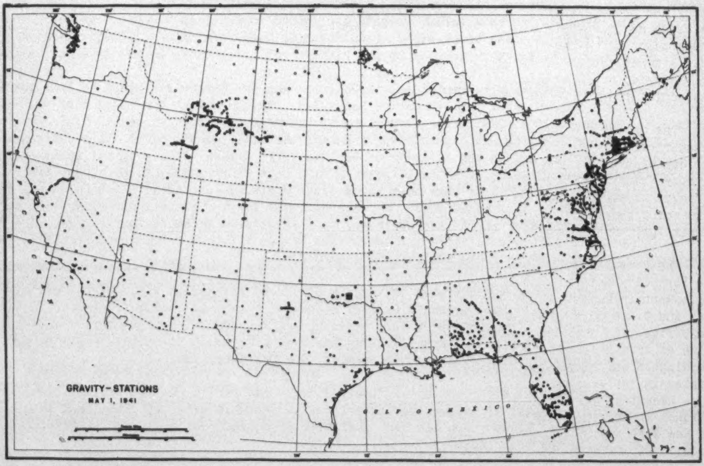
DOMINION OF CANADA
GULF OF MEXICO
GRAVITY-STATIONS
MAY 1, 1941

Fig. 3--Gravity-stations of United States Coast and Geodetic Survey, May 1, 1941

During this present season an attempt has been made to maintain a uniform temperature of the pendulum-apparatus by means of a thermostating device, but considerable difficulty has been experienced because of the large size of the apparatus and unusually severe weather conditions.

A gravity-party is now engaged in cooperative work in Peru, South America. It will probably establish a fundamental base-station for the country and a number of additional stations. A similar project will be carried out in Colombia during the early summer.

A summary of the work accomplished during the past year together with the total amount to date in each classification is given below.

Item	Completed 1940-41	Total to date
Triangulation first- and second-order	2,800 miles	82,000 miles
Leveling, first- and second-order	6,918 miles	284,791 miles
First-order base-lines	1	213
Second-order base-lines	..	54
Latitude-stations	..	854
Longitude-stations	..	705
Azimuth-stations	4	1,172
Gravity-stations	46	1,122

The Bureau has continued the practice of computing the positions of triangulation-stations on the various State Plane-Coordinate systems. Since 1935 all State publications of data concerning horizontal control-surveys issued by the Bureau have given the plane-coordinate position as well as the geographic position (latitude and longitude). This has led to the wide-spread use of the plane-coordinate systems, and indications are that further general use will obtain as the utility and ease of computation of surveys on the State systems become increasingly known.

In six States and in one county the use of State plane-coordinates in the description of private property-boundaries has been given official approval by legislative acts. These States are as follows: New Jersey, 1935; Pennsylvania, 1937; New York, 1939; North Carolina, 1939; Maryland, 1939; Massachusetts, 1941; Georgia, Glynn County, 1940.

Similar legislation is being considered in other States at the present time. In California, a bill adopting the California Coordinate System has passed the Assembly and been referred to the Senate; in Florida a committee of the Florida Engineering Society has been appointed to study and promote such legislation. Considerable interest in a State coordinate act has been or is being manifested in Texas, Iowa, Alabama, Louisiana, Virginia, and Kentucky. In the States where plane-coordinate legislation has been passed, an agency to administer the plane-coordinate act is named either in the act itself, as in New York, North Carolina, Maryland, and Glynn County, Georgia; or in a supplementary act, as in Pennsylvania and New Jersey. In Massachusetts, its administration is assumed by the Land Court in land-boundary cases.

The use of the State plane-coordinate systems is not limited to the description of land-boundaries. State plane-coordinates are extensively used by engineers and surveyors for maps of various classes and different purposes, for example, by engineers for planning of public works, notably the Tennessee Valley Authority, and by surveyors who are making maps of large areas for geophysical study purposes. There is a growing demand for plane-coordinates on the State systems being received from geophysical and oil companies operating in Texas, New Mexico, Louisiana, Mississippi, and Alabama.

The computing offices sponsored by this Bureau as Work Projects Administration projects in New York City and Philadelphia have continued in operation throughout the year with an average employment in each of about 200 persons. The equations for the adjustment of arcs of triangulation and lines of leveling have been formulated by our experienced mathematicians in the Washington Office, and these have then been solved in the New York and Philadelphia offices. Descriptions of triangulation-stations and bench-marks, and lists of geographic positions and plane-coordinates and elevations have been typed in manuscript form in these offices and then lithoprinted in the Washington Office so that these data are readily available for distribution. A large amount of survey-data remained unadjusted at the end of our expanded program under the National Industrial Recovery Act during the years 1932 to 1935. Due to the work accomplished in the New York and Philadelphia offices, much of this has been processed and is now available for issue.

We have cooperated very closely with the United States Geological Survey, Corps of Engineers of United States Army, Bureau of Reclamation, United States Forest Service, and other Government organizations nad have responded to their demands within the limitations prescribed by the funds made available to us. The parties now in the field are engaged in surveys requested by the United States Army and noted as desirable from the standpoint of national defense. During the past year officers of the Bureau were assigned to Fort Bragg, North Carolina, to Fort Benning, Georgia, and were also engaged in the Army maneuvers in Louisiana and Texas. This cooperation has resulted in a better realization and a more comprehensive use of control-survey data by the military agencies. One of our officers was also assigned to the Field Artillery School at Fort Sill, Oklahoma, where he assisted in the preparation of a survey-manual and also instructed Field Artillery officers in surveying methods.

The National Bureau of Standards has continued to standardize invar tapes for us for use in base-measurement and has also continued graduating the circles of theodolites.

The variation-of-latitude observatories at Ukiah, California, and Gaithersburg, Maryland, have continued in operation throughout the year. These two are in a series of five such stations, all on the same parallel of latitude, selected by the International Geodetic Association in order to study the movement of the Earth's axis.

The following publications were either printed during the year or are in press at the present time:

Special Pub. 158, Bilby steel tower for triangulation, revised (1940) edition.
Special Pub. 223, Report on earth tides, 1936-38.
Special Pub. 224, Triangulation in Arizona (1927 datum), Part 1, First- and second-order triangulation in south central part of State.
Special Pub. 225, Manual of reconnaissance for triangulation.
Special Pub. 226, Control leveling.
Special Pub. 227, Horizontal control data.
Serial 347, Use of Coast and Geodetic Survey data in the surveys of farms and other properties, revised (1940) edition.
Serial 632, The preservation of triangulation station marks.

In addition, many lithoprint sheets of descriptions of triangulation-stations and bench-marks, lists of geographic positions, lists of plane-coordinate positions, and lists of elevations of bench-marks have been printed and are ready for issue.

During the coming year we expect to keep the parties now operating at work principally on surveys connected with the national-defense effort and requested by the military authorities.

U. S. Coast and Geodetic Survey,
Washington, D. C.

ON THE STRENGTH OF FIGURES USED IN TRIANGULATION-RECONNAISSANCE

Ching-hai Li

(Abstract)

The strength-of-figure formula now in use in the United States Coast and Geodetic Survey was proposed by J. F. Hayford in 1903. W. H. Burger prepared the table for field-use. It was first applied in field-work by Burger and J. S. Bilby in 1903 and proved so successful that practically all reconnaissance for first-order triangulation is executed in accordance with this method.

The strength-of-figure formula is as follows:

$$R = [(D - C)/D] \sum(\delta_A^2 + \delta_A \delta_B + \delta_B^2) \qquad (1)$$

where R is the strength-factor, δ_A and δ_B are the logarithmic differences corresponding to 1" for the distance-angles A and B, taken in units of the sixth place of decimals, C is the number of geometric conditions, and D is the number of new directions observed.

The principle in least squares, upon which the strength-of-figure formula is based, is the following formula:

$$\mu^2_{\log a} = (2/3)\ \mu^2[(N - C)/N]\ \Sigma(\delta_A^2 + \delta_A\,\delta_B + \delta_B^2) \qquad (2)$$

where $\mu_{\log a}$ is the mean square error of the logarithm of side a of a chain of triangulation-figures (not necessarily triangles), N is the number of angles observed, μ is the mean square error of a measured angle of weight unity, δ_A, δ_B, and C have the same meaning as in equation (1). Equation (2) first appeared in T. W. Wright's "Adjustment of observations," 1884.

C. L. Crandall presented a formula similar to equation (2) in his "Geodesy and least squares," 1907, for triangulation-figures (not necessarily triangles) when observed by the method of directions, as follows:

$$r^2_{\log a} = (4/3)\ d^2\ [(D - C)/D]\ \Sigma(\delta_A^2 + \delta_A\,\delta_B + \delta_B^2) \qquad (3)$$

where d is the probable error of an observed direction, $r_{\log a}$ is the probable error of the logarithm of side a, and other terms have the same meaning as in equation (1).

Equations (2) and (3) are approximate formulas because, first, in finding the probable error of a side in a chain of triangulation-figures, after a single chain of the best-shaped triangles between the base and the side is selected, all tie-lines are rejected. Secondly, the factors [(N - C)/N] in equation (2) and [(D - C)/D] in equation (3) have no theoretical basis. Thirdly, when a triangulation-chain is observed by the method of directions, equation (4), on which equation (3) is based, is not theoretically true.

$$u_{\log a} = (4/3)\ [(D - C)/D]\ \Sigma(\delta_A^2 + \delta_A\,\delta_B + \delta_B^2) \qquad (4)$$

where $u_{\log a}$ is the reciprocal of the weight of the logarithm of side a.

Because of the arbitrary nature of formulas (2) and (3) from which the strength-of-figure formula is derived, this work is undertaken. It is an "empirical" study of the strength-of-figure formula. The purpose is to find how the strength-of-figure formula is related to the probable error of an adjusted side. The method employed is to compute for the several triangulation-schemes the strength of figures, R, and the probable error of an adjusted side, and to compare the two.

The triangulation-schemes upon which the computation of this work is based are from the triangulation-work of the United States Coast and Geodetic Survey. The computation was greatly facilitated by using the old computations made in adjusting the triangulation. Six triangulation-schemes were used. Some are long ones and some short. Some are composed of simple elementary figures, some of complicated ones.

For the purpose of illustration, let us take a chain of quadrilaterals as shown in Figure 1, where angles are shown only to the nearest degree. An arrow along a line represents a Laplace azimuth, and circular broken arcs with arrow heads denote the route through which the functional equation of a side is formed.

Computation is done for each side joining two adjacent quadrilaterals. The table in Figure 2 shows the results of computation. We use P to denote $\Sigma(\delta_A^2 + \delta_A\,\delta_B + \delta_B^2)$, P_1 being for the best chain, and P_2 for the second best. $u_{\log F}$ is the reciprocal of the weight of the logarithm of a side. [vv] is the sum of the squares of the residuals. log F is the logarithm of a side. The units of these quantities are such that they are consistent with the rule that δ_A and δ_B and the logarithm of a side are in units of the sixth place of decimals.

In Figure 3 the square of the probable error of the logarithm of a side is plotted against ΣR_1. In Figures 4 and 5 $u_{\log F}$ is plotted against ΣR_1, and $\Sigma 2P_1/\sqrt{C}$.

From the computations, the following comparisons are made: The square of the probable error of the logarithm of an adjusted side with ΣR_1 and with $\Sigma(\delta_A^2 + \delta_A\,\delta_B + \delta_B^2)$; the reciprocal of the weight of the logarithm of an adjusted side with ΣR_1, with $\Sigma(\delta_A^2 + \delta_A\,\delta_B + \delta_B^2)$ and with $\Sigma(2/\sqrt{C})\ (\delta_A^2 + \delta_A\,\delta_B + \delta_B^2)$.

From the comparisons the following conclusions are drawn:

(1) Equation (3) gives a value of $r^2_{\log a}$ about 20 per cent too small for a chain of quadrilaterals. For a chain of interlocked pentagons or hexagons or other polygons, it may be 30

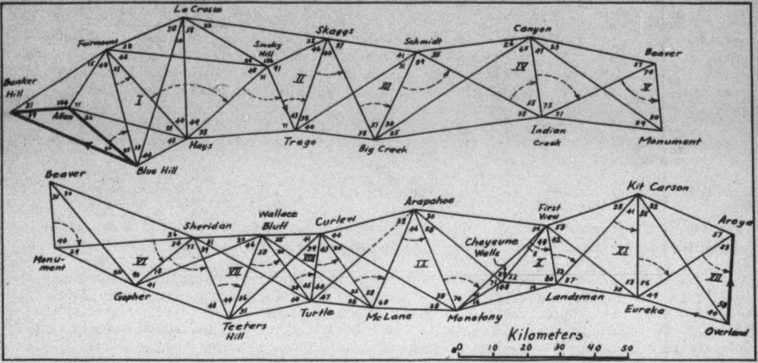
La Crosse
Fairmount
Smoky Hill
Skaggs
Schmidt
Canyon
Beaver
Bunker Hill
Allen
Blue Hill
Hays
Trego
Big Creek
Indian Creek
Monument
I
II
III
IV
V
Beaver
Sheridan
Wallace Bluff
Curlew
Arapahoe
Cheyenne Wells
First View
Kit Carson
Aroya
Monument
Gopher
Teeters Hill
Turtle
McLane
Monotony
Landsman
Eureka
Overland
VI
VII
VIII
IX
X
XI
XII
Kilometers
0
10
20
30
40
50

Fig. 1--This triangulation-scheme is taken from "Office computation of triangulation, 39th parallel arc, States of Kansas and Colorado" [Archives and Library of United States Coast and Geodetic Survey]

		1 Angle Conditions	2 Side Conditions	3 C	4 New Directions, D	5 $\frac{D-C}{D}$	6 P_1	7 P_2	8 R_1	9 R_2	10 $\frac{\sqrt{C}}{2}$	11 $\frac{2P_1}{\sqrt{C}}$	12 ΣP_1	13 ΣR_1	14 $\Sigma\frac{2R_1}{\sqrt{C}}$	15 $u_{\log F}$	16 $[vv]$	17 ΣC	18 $\frac{[vv]}{\Sigma C}$	19 $(p.e.)^2$ of an Obs. Dir.	20 $(p.e.)^2$ of log F
I	Fairmount-Hays	3	1	4	10	·60	4	5	2·0	2·5	1.22	3.3	4	2	3	2·9	3.96	6	.660	·300	·875
II	Skaggs-Trego	3	1	4	10	·60	19	28	10.4	15.4	1.66	11·5	23	12	15	16·0	10·91	17	·642	·292	4.67
III	Schmidt-Big Creek	4	2	6	12	·50	5	10	3·0	6·0	1.00	5·0	28	15	20	22.4	12.58	21	·598	·272	6·10
IV	Canyon-Indian Creek	5	3	8	17	·53	25	29	15·0	17.4	1.00	25.0	53	30	45	44.8	13.98	25	·559	·254	11.40
V	Beaver-Monument	5	2	7	16	·56	25	35	15·0	21.0	1.00	25.0	78	45	70	68.6	14.27	29	·492	·284	15·56
VI	Sheridan-Gopher	3	1	4	10	·60	31	34	18·6	21·6	1.00	31.0	109	64	101	97.9	15·93	33	·483	·220	21.52
VII	Wallace Bluff-Teeters Hill	3	1	4	10	·60	11	20	6·6	12·0	1.12	9.8	120	71	111	109.9	16·72	38	·440	·200	22.00
VIII	Curlew-Turtle	4	2	6	12	.50	7	15	3·5	7.5	1.22	5.7	127	74	116	115·8	18.42	44	·419	.190	22.07
IX	Arapahoe-Monotony	5	3	8	17	·53	10	21	5·3	11·1	1.42	7.1	137	79	123	127.1	20.15	52	·387	.176	22.40
X	First View-Landsman	5	2	7	16	·56	22	22	12·3	12·3	1.32	16·6	159	92	140	143.5	24.7	59	·419	·191	27.37
XI	Kit Carson-Eureka	3	1	4	10	.60	15	16	9.0	9·6	1.00	15·0	174	101	155	158.8	25·2	63	.400	·182	28.90
XII	Aroya-Overland	3	1	4	10	·60	8	14	4.8	8.4	1.00	8.0	182	106	165	167.8	26·2	67	·390	·178	29.81

Fig. 2

per cent too large.

(2) for a chain of quadrilaterals, ΣR_1, has an approximately linear relation with the square of the probable error of the logarithm of an adjusted side, if we assume that the probable error of an observed direction is the same for the different chains. Thus, ΣR_1 has an approximate linear relation with the square of the probable error of a unit length of the side.

(3) For a chain of quadrilaterals, equation (5) is true within eight per cent in all but a few cases.

$$u_{\log a} = (5/3)\ \Sigma R_1 \tag{5}$$

(The unit of $u_{\log a}$ is such that it is consistent with the rule that the logarithm of a side is expressed in units of the sixth place of decimals.) Thus, the strength-of-figure formula proves

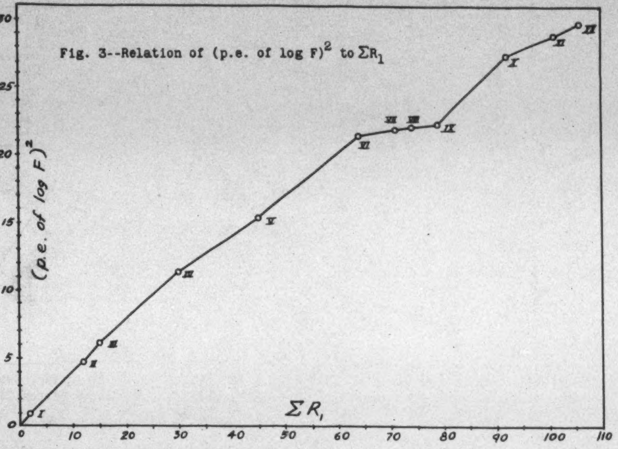
Fig. 3--Relation of (p.e. of log F)^2 to ΣR_1

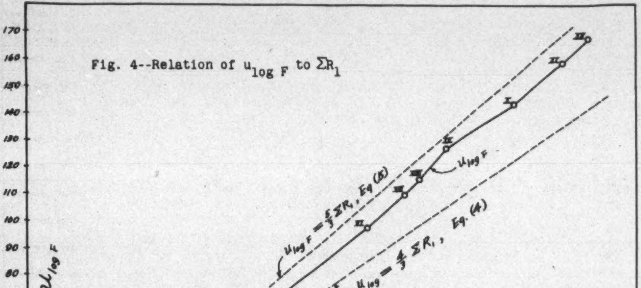
Fig. 4--Relation of $u_{\log F}$ to ΣR_1

to be fairly good in representing in some way the reciprocal of the weight of the logarithm of an adjusted side.

(4) For a chain of quadrilaterals, the equation

$$u_{\log a} = \Sigma(2/\sqrt{C})\,(\delta_A^{\,2} + \delta_A\,\delta_B + \delta_B^{\,2}) \tag{6}$$

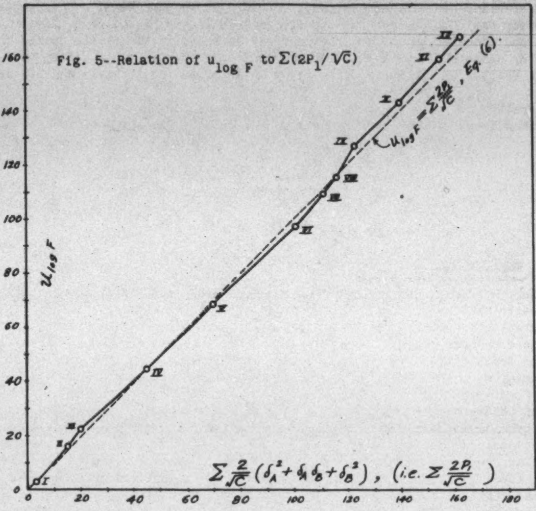

Fig. 5--Relation of $u_{\log F}$ to $\Sigma(2P_1/\sqrt{C})$

is correct within four per cent in all but a few cases. Therefore, it is more nearly true than equation (5) in representing the reciprocal of the weight of the logarithm of an adjusted side. A new strength-factor, S, defined by the formula

$$S = (2/\sqrt{C}) (\delta_A^2 + \delta_A \delta_B + \delta_B^2) \tag{7}$$

is proposed by the writer. He does not, however, suggest that the use of equation (1) be abandoned in survey-organizations where equation (1) has been a traditional practice.

(5) With the help of equations (5) and (6), the strength of a figure, or of a chain of figures, gains a quantitative meaning. If we make the assumption that the mean square error of an adjusted quantity be equal to the true error of the adjusted quantity, we can compute how close the agreement between the base-lines would probably be, corresponding to a ΣR_1 or ΣS_1. Taking the probable error of an observed direction to be 0".3, $\Sigma R_1 = 80$ thus represents an agreement between base-lines of one part in 84,500 and $\Sigma R_1 = 110$ represents one of one part in 72,000. The limit of ΣR_1 for first-order triangulation can, it seems, be safely extended to 110 or even more without danger that the disagreement between bases will exceed 1/25,000.

(6) If chains of polygonal figures are to be used in triangulation, further investigation and resetting of the limit of ΣR_1 will be necessary.

(7) One is justified in saying that "the greater the number of conditions the stronger will be the figure, and that the second best chain of triangles in a triangulation-scheme contributes somewhat to the total strength, which, however, depends mainly upon the best chain" [Special Pub. 120, U. S. Coast Geodetic Surv.].

(8) The writer believes that in calculating R, accurate interpolation in the table for $(\delta_A^2 + \delta_A \delta_B + \delta_B^2)$ is unnecessary and at the same time impossible. Only whole numbers (that is, integers) should be used. R, however, should be carried to one decimal place to ensure that ΣR be correct to one unit.

(9) It seems to the writer that in triangulation-adjustment the length-equation can be formed from any chain of triangles, not necessarily the best chain. A most direct chain of triangles seems desirable, for few multiplications will be involved and it will not be detrimental to accuracy.

The writer wishes to express his gratitude for the encouragement and suggestions given to him by Professor Paul H. Underwood of Cornell University and by Walter D. Lambert of the United States Coast and Geodetic Survey, for the courtesy extended to him by the United States Coast and Geodetic Survey whose Archives and Library were placed freely at his disposal, and for the help of Charles A. Whitten of the Survey in finding material in the Archives and Library.

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A TRANS-CONTINENTAL GRAVITATIONAL TRAVERSE AND ITS RELATION TO REGIONAL GEOLOGY

George P. Woollard

(Abstract)

The writer, working under a grant from the Geological Society of America and using a Humble type-X gravimeter made available to the American Geophysical Union for scientific research, established a gravitational traverse from Morro Bay, California, to Sea Bright, New Jersey. The traverse crossed the San Joaquin Valley, Death Valley, the Basin and Range Area, the Rocky Mountains, the Great Plains, the Ozark Uplift, the Illinois Basin, the Cincinnati Arch, the Appalachian Mountains, the Triassic lowlands, and the Atlantic Coastal Plain.

A line of base-stations was first established at intervals of about 35 miles across the Continent. These bases were occupied so as to form a series of closed loops with each station tied by repeat observations to the preceding and following stations. This was necessary in order to establish the drift-characteristics of the instrument. The final traverse was run with stations at a five- to six-mile interval, and errors in closure and drift were adjusted by comparing the base-station gravitational interval observed with the values originally obtained on the outward traverse.

The results of the traverse indicate that the country can be roughly divided into two parts, with the dividing line near the Kansas-Missouri Border. In the eastern half, no definite correlation is to be observed between structural geologic features except that the structural "highs" and "lows" appear to have an inverse reflection in the gravity-profile. An exception is the Appalachian trough which is characterized by a gravitational trough which centers in the Blue Ridge Mountain Region. These relations are evident in both the Bouguer and isostatic anomaly-values. In the western half of the country there is a tendency, from the Basin and Range Region to the Pacific area, for the gravity-values to conform with the geologic structure. There are certain anomalous areas, though, such as in the San Joaquin Valley where a marked gravitational "high" occurs in an area that is structurally low. In the mid-Continent area features such as the Nemeha granite ridge cause no marked gravitational disturbance, although, a few miles to the west of the ridge, a marked gravitational high occurs in the Salina Basin Area. All of the country is apparently characterized by gravitational "highs" and "lows" whose dimensions, roughly about 40 miles across, rule them out as being associated with either regional or local geologic structural features, and presumably these are a reflection of changing lithology in the basement crystalline rocks. For the most part they appear to be relatively deep-seated and one in particular, the Blue Ridge trough, may be a reflection of the configuration of the bottom of the upper crust.

Whereas in the eastern part of the Continent the isostatic effects are for the most part small, in the western part of the country the isostatic effects are extremely large. In the Rocky Mountain Area the isostatic correction exceeds 250 milligals and the isostatic anomaly-values show this area to be gravitationally high in contrast to the Appalachian Mountain Area where the isostatic values show this area to be gravitationally low.

For local geologic structural studies, some sort of regional correction appears to be necessary everywhere with larger residual values being left in the western area than in the east.

This work will be reported in full in a forthcoming bulletin of the Geological Society of America.

Princeton, New Jersey

GRAVITY AND MAGNETIC STUDIES ALONG THE PALEOZOIC-TRIASSIC CONTACT IN EASTERN PENNSYLVANIA

J. B. Hersey

During the past year a project of geophysical field-work has been started in the area along the Paleozoic-Triassic contact in Eastern Pennsylvania. The purpose of this report is to outline the general problem, describe the methods being used and some of the results already obtained.

The area being studied at present extends from the Delaware River westward along the northern boundary of the Triassic belt to a distance about five miles south of Emmaus and six miles northwest of Quakertown in Pennsylvania. The object of the survey is to study the nature of the contact between the Pre-Cambrian and Paleozoic and the Triassic sediments in this region and to outline the trap-rock intrusives in the Triassic. At present, gravitational and magnetic methods are being used.

Measurements of gravity have been made using the Humble gravimeter now on loan by the Humble Oil Company to the American Geophysical Union. Magnetic measurements have been made with Askania vertical magnetometers.

The gravimeter was calibrated in this survey by reoccupying stations established during the summer of 1935 by the United States Coast and Geodetic Survey. Figure 1 shows the results of one of two such calibrations that have been made in the course of field-work this spring. The circles represent observed gravity as published by the United States Coast and Geodetic Survey plotted against readings on the arbitrary scale of the gravimeter. The Humble gravimeter is being operated at a low sensitivity for this work so that one scale-division on its arbitrary scale is equivalent to 0.375 milligal.

One hundred and twenty gravity-stations have been established in the central part of the area outlined giving a grid of stations every half to one mile apart. These cover an area of about 40 square miles, 12 miles long and three to four miles wide. Approximately half the stations were occupied last fall and the remainder this spring. Reoccupations this spring of

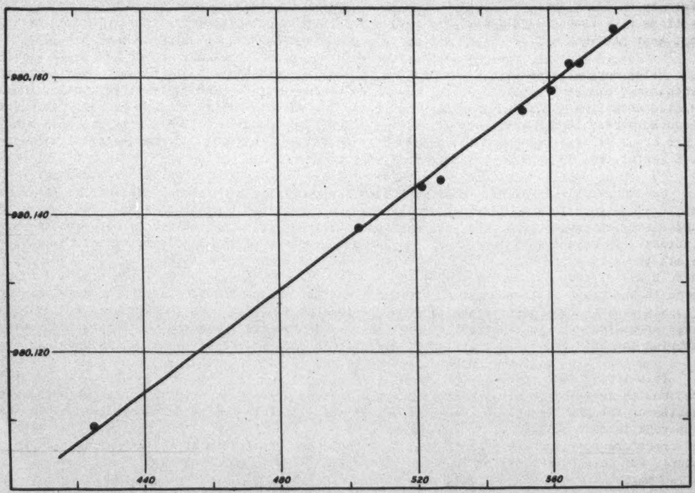

Fig. 1--Gravimeter-calibration, Eastern Pennsylvania, April, 1941
(Scale-constant, 0.375 milligal per scale-division)

several of the stations made last fall indicate an uncertainty of ±0.4 milligal in the observed values of gravity. The majority of the reoccupations showed absolutely no difference from fall to spring.

The locations of stations were determined by plotting positions on Geological Survey quadrangle maps. The normal latitude-correction in the latitude of Pennsylvania is +1.287 milligals per mile southward. The stations are located to better than one-tenth of a mile, so that latitude-corrections are accurate to about 0.1 milligal.

So far the elevations of the stations have been read from the quadrangle maps as well. In order to improve the reliability of this method stations have been located at road intersections in nearly every case. Frequently it has been possible to locate on intersections for which the elevations are published on the maps, and occasionally locations have been made at railroad stations. It will be obvious from this that the elevation-data are the most unsatisfactory, and it is hoped that more reliable means will be available for checking this part of the survey soon.

Nevertheless, it is thought likely that few of the elevations are out as much as ten feet although a few may be as far out as 20 feet.

Density-measurements on a small suite of samples from the area give the following values for density of the main rock-types:

Pre-Cambrian:	Byram gneiss,	2.7	Triassic:	Sediments,	2.5-2.8
	Pochuck gneiss,	2.8		Trap-rock,	3.0
Paleozoic:	Limestone,	2.7			

Three density-profiles have been made over Pochuck gneiss, Triassic sediments, and trap-rock following the procedure outlined by Nettleton [see 1 of "References" at end of paper]. These corroborate the above measurements, but in all cases they prove not to be entirely satisfactory as density-profiles, so that the results are not conclusive.

The observed gravity-values have been reduced for latitude-, elevation-, and Bouguer-effects. Correction for the effect of terrain has been made in the case of only a few stations. All stations have been located to minimize terrain-effects, and stations selected for this preliminary calculation were chosen to be those that should have the largest correction. The corrections have been made using Hammer's table [2]. Results of this preliminary check indicate that most stations will have terrain-corrections of the order of less than half a milligal.

Using Bouguer anomalies calculated from the data that have just been described, a gravity contour-map has been made. Mainly because of the uncertainty in elevation-data behind the calculated anomalies, this map is being used only as a guide for further work and will not be reproduced here. It may be stated, however, that gravity-anomalies show a distinct relation to known areas of trap-rock, and in general the indications are that the gravitational method will be a useful tool in studying local structure in this area.

Schmidt vertical balances have been used in two magnetic surveys of the area. The first was of the nature of a reconnaissance-survey. It was made last fall and covered a considerably larger area including the Saucon Valley and the surrounding Pre-Cambrian hills. In this survey stations were established every mile and, as this area is highly disturbed magnetically, it will be all the more appreciated that this is the roughest sort of reconnaissance. It served to show, however, that the main disturbing factor in Triassic areas is the trap-rock, and that there is an abrupt difference in the order of magnitude of magnetic changes in going from the Triassic or from Paleozoic limestone to the Pre-Cambrian areas. In the Triassic or limestone areas anomalies are readily shown with a contour-interval of 100 gammas in Z. In the Pre-Cambrian the only contour-interval justified for this rough survey was 1,000 gammas.

This spring vertical magnetometers have been used for detailed mapping of the edges of trap-bodies near the Triassic-Paleozoic contact. The purpose of this is primarily to check the results of the gravity-survey in relation to trap-rock distribution. Geological mapping of the trap-rock is made uncertain by the necessity of mapping on the basis of float in this region, and therefore previous geological work is valuable mainly in showing where the areas of trap occur. For this reason and because it is desirable to know the exact limits of the trap, a detailed magnetic survey is projected to outline trap-bodies in the area. This program is actually barely begun, but enough data have been accumulated to show typical profiles of the magnetic disturbance near the edge of trap-bodies in the area. The profiles shown on Figure 2 are made roughly perpendicular to the contact-zone between the trap and the sediments. At this place the zone strikes roughly east-west. Figure 2 is a plan view, the horizontal lines indicating the location of the profiles shown. Near the contact-zone stations are established every 200 feet and away from it every 400 feet on most of these profiles. The pronounced magnetic high over the trap-side of the contact-zone and "low" over the sediment-side is seen to be strikingly characteristic of the profiles. The contact is to be placed between the "low" and the "high." It is not certain just how closely the contact-zone can be determined in all cases, but it seems likely that it can be located within 25 to 50 feet in some cases, and not so closely in others. In all cases where this type of profile is persistent it will be possible to map the contact-zone with considerably more assurance than from geological evidence alone.

In addition to the mapping of the trap, magnetic surveys of the whole area are planned. They will be as detailed as is required by the data, and results will be compared with the gravity-results. Plans for the immediate future include extending the area of the gravity-survey eastward to the Delaware, and farther to the southwest if possible. More precise elevation-measurements are to be obtained for all gravity-stations, and further density-studies are to be made. Also, it would be highly desirable to extend the net of stations already started by the United States Coast and Geodetic Survey to the north and west of Blue Mountain. This should be done particularly to the northwest where gravity-stations are very sparse indeed. Such a filling out of the regional picture would be useful not only in this and nearby local surveys now being made, but would also be of interest in the general problem of Appalachian structure.

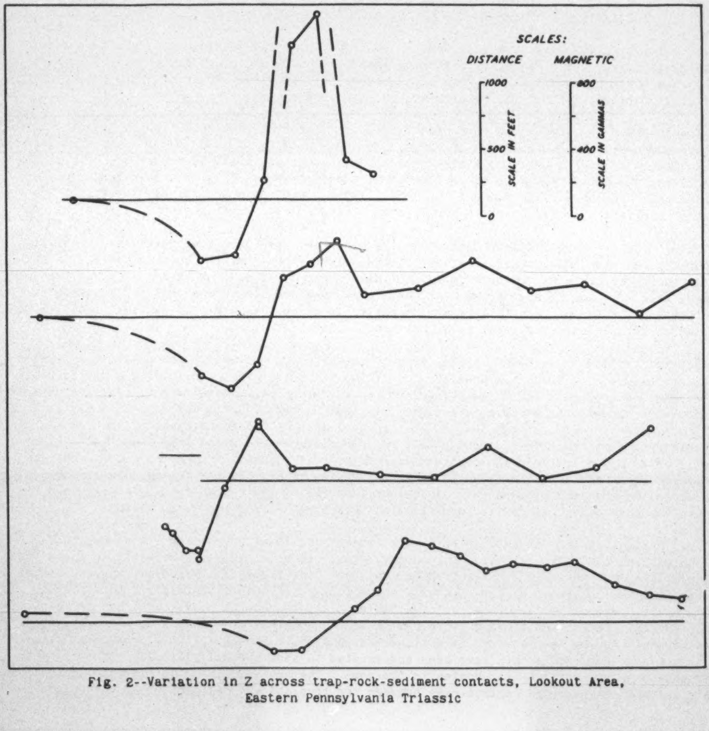

Fig. 2--Variation in Z across trap-rock-sediment contacts, Lookout Area, Eastern Pennsylvania Triassic

Acknowledgments--The writer wishes to thank the American Geophysical Union for the use of the gravimeter in this project and Dr. G. P. Woollard for the use of his magnetic field-equipment. G. A. Rynearson and E. W. Roedder of the Geology Department of Lehigh University have been of great assistance in the field-work and computations. Their continued help on this project is very much appreciated.

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[1] L. L. Nettleton, Determination of density for reduction of gravimeter observations, Geophysics, v. 4, pp. 176-183, 1940.
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A GRAVITY-PROFILE ACROSS THE CENTRAL APPALACHIANS, BUCKHANNON, WEST VIRGINIA, TO SWIFT RUN GAP, VIRGINIA

Sigmund Hammer and E. T. Heck

Introduction--In recent years a considerable amount of geophysical work in the northern Appalachians and eastward across the crystalline rocks of the Piedmont and the Atlantic Coastal Plain has been reported and discussed, notably by Ewing [see 1, 2, 3 of "References" at end of paper], Leet [4], Longwell [5,6], Miller [7], Nettleton [8], Straley [9], Swick [10,11], and Woollard [12-18]. Thom [19] has stated that this is one of the most favorable testing grounds in the world for geophysics in the study of fundamental geological problems as a great variety of gentle and steep folds, faults, and types of rock are encompassed in a relatively narrow belt. The present paper adds to the geophysical study of this geologic province by presenting the results of a closely spaced profile of gravimeter-stations across the central Appalachians. The work was done at the specific suggestion of Dr. Paul H. Price, State Geologist of West Virginia, to Dr. E. A. Eckhardt of the Gulf Research and Development Company. The desirability of such work has been recognized for some time [10,19,20].

The gravimeter-profile presented herein follows United States Highway 33 from Buckhannon, West Virginia, to Swift Run Gap, Virginia, and crosses the entire folded sedimentary section of the central Appalachians from gently folded Pennsylvanian sediments of the Appalachian Plateau on the west onto the crystalline pre-Cambrian rocks at the Blue Ridge. The profile is about 150 miles long by road but the air-line geologic section spanned is shorter--about 102 miles. There are 101 gravimeter-stations in the profile; hence, the average projected distance between stations is about one mile. The present profile is practically a westward extension of Ewing's [1], Woollard's [15], and Swick's [10] Cape Henry seismic, magnetic, and gravity profile.

Gravity-observations--The gravity-observations were made with a standard Gulf gravimeter as described by Wyckoff [21] which was calibrated against a known gravity-difference determined to a probable error of one-fifth per cent by Gulf pendulum apparatus [22].

The relative gravity-values of the gravimeter-stations were determined as follows: First a series of subbases spaced roughly ten miles apart was selected and observed with the gravimeter according to the "loop" scheme illustrated in the upper left of Figure 1. Typical data are shown in the lower left of the Figure. This scheme of operations greatly reduces any error due to irregular drift of the gravimeter or to tidal gravity-variations because the time-interval between observations at any one station is short--not over one or two hours--and has the added advantage that the ties between subbases are completed one by one. The precision of the tie is indicated by the parallelism of the two overlapping segments of the drift-curve and by the gravity-scale in Figure 1.

Having observed the subbases from west to the east along the profile, the intermediate stations were next observed continuously from east to west by the scheme illustrated in the upper right of Figure 1. (The intermediate stations are indicated by hyphenated numbers.) The gravimeter-drift is calculated from readings at the successive subbases together with the known gravity-difference between subbases. Typical data are shown in the lower right of Figure 1.

The performance of the gravimeter during the whole course of these observations was such that the precision of the observed relative gravity-values is about 0.1 mg. However, the

Table 1--Determination of absolute gravity-datum for gravimeter-data

U.S.C.and G.S. pendulum-station	Observed from subbase	U.S.C.and G.S. observed g	Δg re gravimeter-datum	Calculated gravimeter-datum value	Gulf g at U.S.C.and G.S. station	Difference
		mg	mg	mg	mg	mg
260	1	980,013	+58.22	979,954.78	980,011.52	-1.48
328	12	979,858	-95.95	979,953.95	979,857.35	-0.65
331	4-4	979,899	-54.42	979,953.42	979,898.88	-0.12
397	12	979,947[a]	- 3.99	979,950.99	979,949.31	+2.31
Average				979,953.28	±0.55	
Adopted				979,953.30		

[a] Revised value in personal communication from J. H. Hawley of United States Coast and Geodetic Survey.

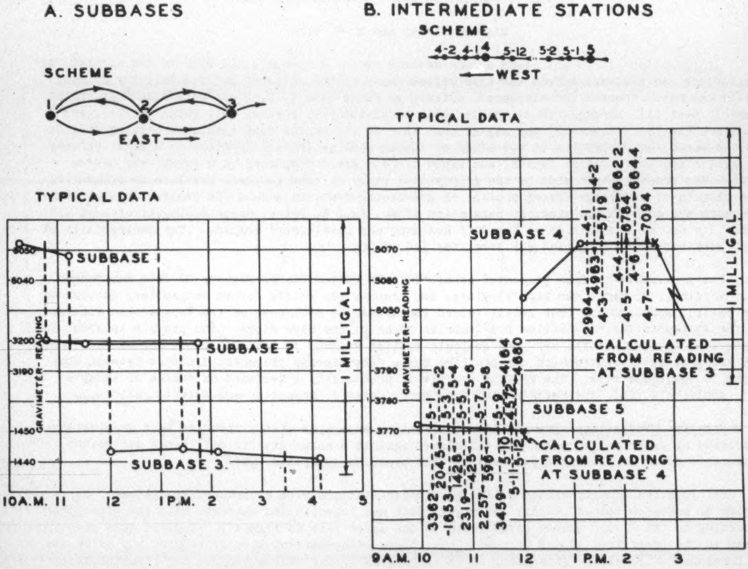

Fig. 1--Method of observation

gravity-range was so large (172 mg) that the inaccuracy in the absolute gravimeter-calibration becomes appreciable. Even making this allowance it is probable that the gravimeter-data are accurate to a few tenths of one milligal.

The absolute gravity-datum for the gravimeter-stations was determined by ties into four United States Coast and Geodetic Survey pendulum-stations as shown in Table 1. It would appear that the absolute gravity-datum referred to the adopted United States Coast and Geodetic Survey value for Washington, D. C., is probably not in error by over one milligal.

Station-reductions--The stations were reduced by Bullard's modifications [23] of the

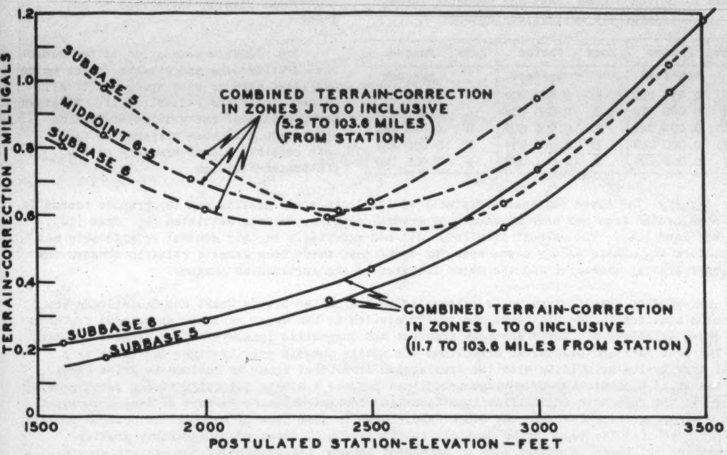

Fig. 2--Method of interpolating terrain-corrections

United States Coast and Geodetic Survey method with an assumed uniform density of 2.67 and with reference to the 1930 International Gravity Formula [24]. The only novel feature in the reduction is the development of an interpolation technique for the terrain-corrections (that is, that part of the topographic correction which is due to undulations of the topography above and below the elevation of the station) which permitted interpolations for "zones" near the station and thus saved much labor in reducing the closely spaced profile-stations. The technique employed was as follows:

(1) Outside Zone O the combined correction for topography and compensation was read from a contour-map of the United States Coast and Geodetic Survey corrections on all pendulum-stations in the general vicinity of the present gravimeter-profile.
(2) For the subbases, which we recall are about ten miles apart, the terrain and isostatic corrections were computed directly out to the end of the United States Coast and Geodetic Survey Zone O (outer radius 166.7 km--103.6 miles).
(3) For a midpoint station between each pair of subbases the terrain and isostatic corrections were determined directly to the end of Zone K (outer radius 18.8 km--11.7 miles) and the corrections in the outer Zones L to O interpolated.
(4) For all remaining intermediate stations the terrain and isostatic corrections were determined directly to the end of Zone I (outer radius 8.44 km--5.2 miles) and the corrections in the outer Zones J to O interpolated.

The interpolation of the terrain-correction allows for its variation with height of the station by the following technique: The terrain-corrections on the subbases and midpoint stations were calculated in the outer zones for several postulated elevations of the stations and curves of terrain-correction versus postulated station-elevation were drawn as illustrated in Figure 2. Then the values appropriate to the elevation of the intermediate station were read from the curves for the two basic stations and interpolated on the basis of the relative distances to the station. As illustrated by the curves in Figure 2, the interpolated increments are very small (rarely exceeding one-tenth mg) and direct checks show that the interpolated terrain-corrections (for the station-spacing and zone-selection used here) are no less accurate than the corrections determined directly.

The isostatic corrections were calculated by multiplying the average topographic elevations in the various zones by the coefficients given in Table 2 which were kindly supplied by the United States Coast and Geodetic Survey and published here as a matter of record with the Survey's permission. The interpolation of the isostatic corrections is straightforward as the individual station-elevations do not enter.

The complete tabulation of the numerical gravity-data and results is not being published here to save space but it will be sent to anyone requesting it. Detailed descriptions of the gravimeter-station sites also have been prepared to facilitate possible future recovery of the gravimeter-stations.

Table 2--United States Coast and Geodetic Survey isostatic correction-factors

Zone	Factor	Zone	Factor	Zone	Factor
	mg/foot		mg/foot		mg/foot
A	0.000 000	F	0.000 303	K	0.001 677
B	0.000 020	G	0.000 365	L	0.002 409
C	0.000 049	H	0.000 503	M	0.005 848
D	0.000 109	I	0.000 914	N	0.005 324
E	0.000 209	J	0.001 092	O	0.005 178

Results--The close regional conformity of the large-scale gravity and topographic trends in the Appalachian area has been discussed by several authors, notably Nettleton [8], Thom [19], and Woollard [14]. The present results do not add materially to this general relationship but do confirm it. There hardly seems room for doubt that there is a genetic relation between the regional gravity-anomalies and the major features of the Appalachian orogeny.

The present gravity-results (supplemented by the United States Coast and Geodetic Survey pendulum-stations in the vicinity) and their relation to the major geologic structural features are shown in Figure 3. There are some apparent and suggestive local relations between the two: (1) The Deer Park and Blackwater anticlines lie within a broad gravity-high; (2) there is a local gravity-low coinciding with the Appalachian structural front as defined by Price [25]; (3) the Wills Mountain and Long Ridge anticlines produce a single but quite strong local gravity-high; (4) the Paleozoic-crystalline (pre-Cambrian) contact exposure is more or less coincident with a strong gravity-low. On the other hand, there is some lack of correlation between gravity and geology: (1) The major North Mountain overthrust-fault shows no recognizable gravity-expression; (2) there is enough lack of agreement between the details of the eastern gravity-low and the Paleozoic-crystalline contact to raise doubts about any direct physical relation between the two. These apparent relations, as judged from a map only, may be illusory and can be judged better on a cross-sectional view.

Figures 4-A and 4-B show the gravity-results in detail and the geologic cross-section projected onto the straight lines AB and CD of Figure 3. The offset in the road from B to C is quite accurately parallel to the geologic strike and produces only a minor break in the curves. There are several other smaller offsets in the profile which are indicated on Figures 4-A and 4-B but the general continuity of the gravity-results is shown by the parallelism of the projected segments of the gravity-curves.

The structural cross-section as inferred from surface geology is drawn to approximately natural scale, that is, no vertical exaggeration. The lowest pair of curves show the Bouguer Anomaly--the lower, dashed curve without terrain and Bullard's curvature [23] corrections (the "simple" Bouguer Anomaly) and the upper, solid curve with complete corrections for topography out to the end of Zone O. The difference between these two curves illustrates the significant errors which may be present in "simple" Bouguer-Anomaly values in mountainous country. The Bouguer-Anomaly values are remarkably constant over the entire profile with a total variation from -52 to -64 mg and an average of roughly -60 mg. The next two curves show the isostatic gravity-anomalies calculated on the assumption that the depth of compensation is 113.7 km. The dashed line shows the conventional isostatic anomaly values and the solid line shows arbitrarily smoothed values to distribute the isostatic correction for strictly local topographic features and to smooth out the inaccuracies in the isostatic corrections in the large distant topographic zones. (The smoothing was done in the belief that topographic features less than, say, ten miles wide are almost certainly not isostatically compensated and that the ordinary isostatic anomalies might be incorrect in detail on that account. However, the procedure of the Geodetic Survey of India [26] of making no isostatic correction whatever for the topography near the station is logically inconsistent as it assumes different isostatic conditions for the same topographic feature depending upon its distance from the station.) The character of the smoothed and unsmoothed curves is so similar that their differences are not of any qualitative significance. It is possible that Vening-Meinesz's regional isostatic corrections [27] might lead to different results but they have not been calculated for these data. The isostatic anomaly-values vary from about -5 mg near the western end of the profile to about -35 mg near the eastern end. The strong rise farther east as shown by United States Coast and Geodetic Survey data apparently begins just east of the profile (see Fig. 3). The station-elevation and Free-Air-Anomaly curves appear at the top of the Figure. Note that the ordinate scale for the Free-Air-Anomaly is only one-fourth as large as for the Bouguer and isostatic anomalies. The Free-Air-Anomaly values tend to be positive but sometimes become negative. The perfect correlation between station-

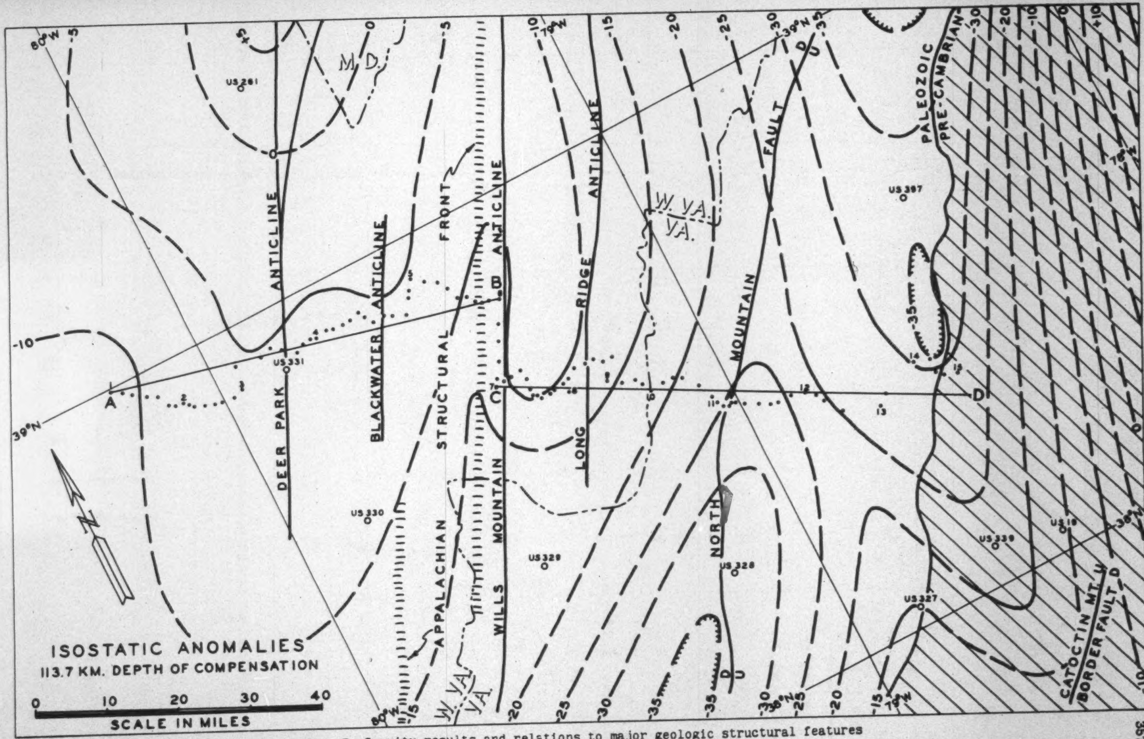
ISOSTATIC ANOMALIES
113.7 KM. DEPTH OF COMPENSATION
0
10
20
30
40
SCALE IN MILES
N
80°W
79°W
78°W
39°N
39°30'N
38°30'N
A
B
C
D
DEER PARK
ANTICLINE
BLACKWATER ANTICLINE
APPALACHIAN STRUCTURAL FRONT
WILLS MOUNTAIN ANTICLINE
LONG RIDGE ANTICLINE
NORTH MOUNTAIN FAULT
PALEOZOIC
PRE-CAMBRIAN
CATOCTIN MT.
BORDER FAULT
U
D
M.D.
W. VA.
VA.
US 261
US 331
US 330
US 329
US 328
US 397
US 327
US 339
US 19
+5
0
-5
-10
-15
-20
-25
-30
-35
+10

Fig. 3--Gravity results and relations to major geologic structural features

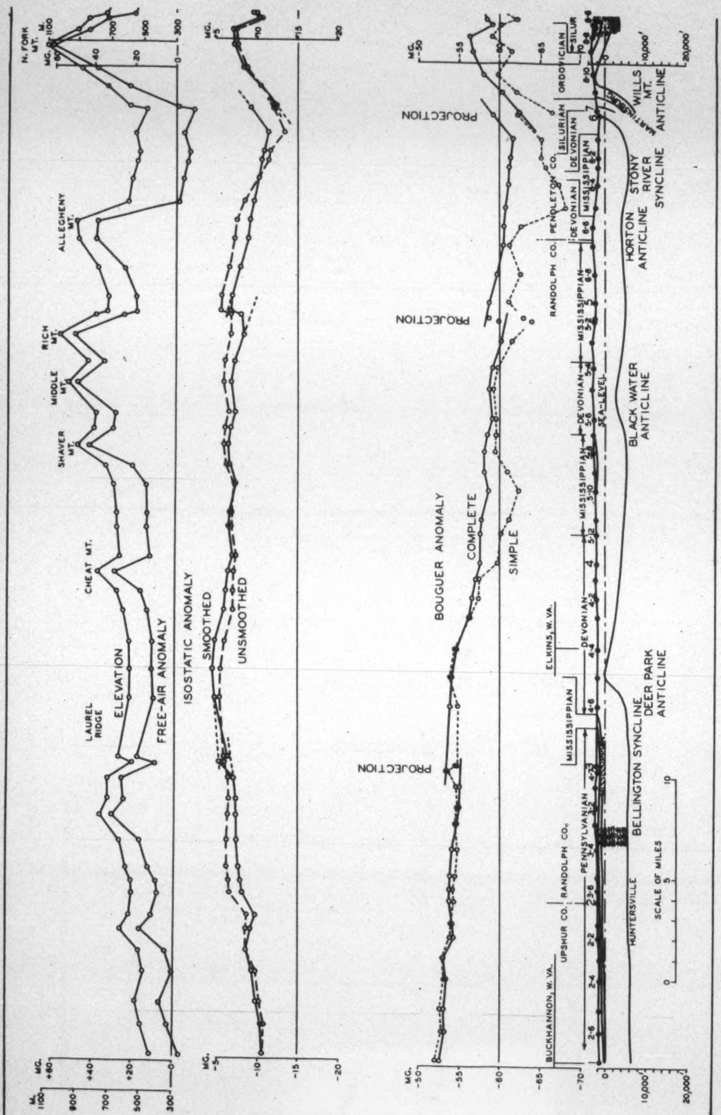

Fig. 4-A--Geologic cross-section and details of gravity results (west half)

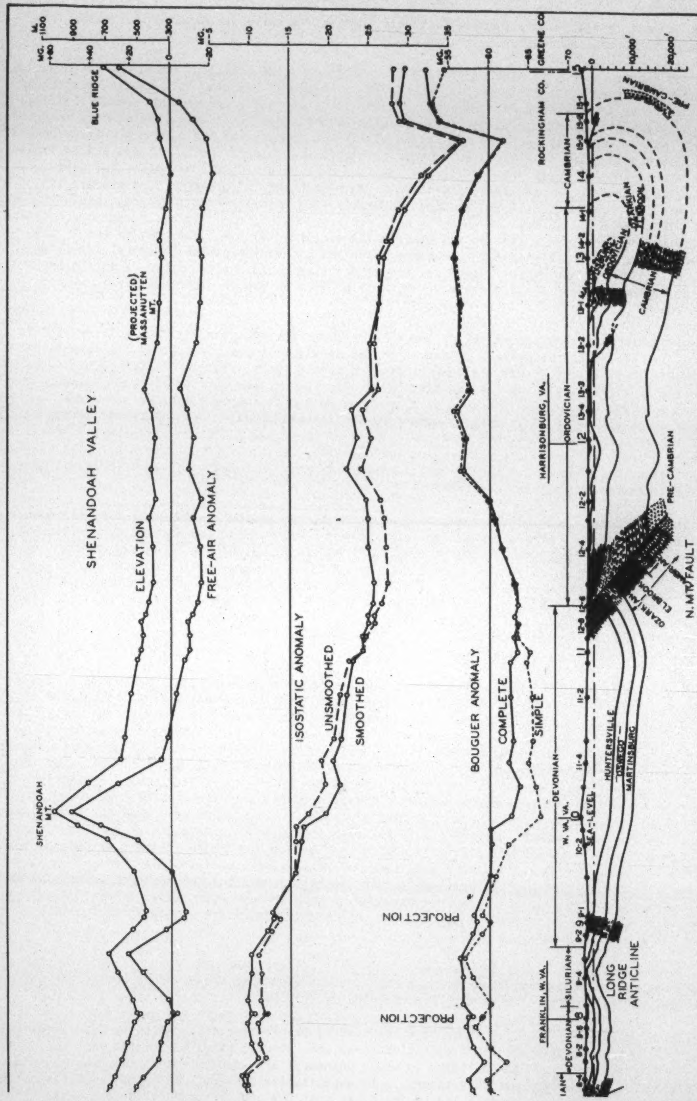

Fig. 4-B--Geologic cross-section and details of gravity results (east half) elevation and Free-Air-Anomaly shows that this quantity is quite worthless in revealing local geologic structural conditions.

The sectional view in Figures 4-A and 4-B brings out some relations which are not apparent on the map in Figure 3. For example: (1) The coincidence of the Deer Park anticline with the broad westerly gravity-high noted on Figure 3 is almost certainly fortuitous because the local gravity-expression which can be ascribed directly to this fold (within the sedimentary section) is very small (certainly not over one or two mg) if not absent; (2) the single gravity-high over the Wills Mountain and Long Ridge anticlines is surprising because the anticlines are sufficiently separated so that their gravity-expressions should be resolved [28] if they arise from density-contrasts in the sedimentary section. The resolution, if present, is certainly not clear with the present data; (3) the apparent gravity-low coincident with the Appalachian Structural Front has no local reality as it is only the resultant of the "regional" eastward decrease in gravity and the gravity-high at the Wills Mt. Anticline; (4) the local gravity-low at the eastern end of the profile is much too sharp to be the expression of the relatively broad sedimentary syncline adjoining the outcrop of the crystalline rocks. (This sharp feature does not seem to be shown by the closely spaced gravimeter-profile across the Appalachians in Pennsylvania [8].)

Discussion and conclusions--While there is little doubt that the regional gravity-picture is closely related to the general tectonics in the Appalachian area, it slowly has come to be realized [3,5,8,11,15,19] that the gravity-picture cannot be fully accounted for by simple considerations of lithologic changes and structures observed or deduced from surface-geology. The present detailed data go much farther as they prove an almost complete lack of local gravity-anomaly associated with individual structure in the central Appalachians. This can hardly lead to any other conclusion than that practically none of the gravity-picture arises within the sedimentary section and therefore that it must be due almost entirely to structural or lithologic changes below the sedimentary layer. (Fortunately for gravitational geophysical prospecting this condition does not exist everywhere.)

The absence of local gravity-anomalies over the strong geologic structures can only mean that density-contrasts within the sedimentary section compensate or are lacking. Nettleton [8] has concluded that the latter is the case in the Northern Appalachians. The only apparent exception to this conclusion in the present results is the sharp gravity-low culminating at station 15-3 near the extreme eastern end of the profile which suggests that there may be a low-density member in the Cambrian section. Station 15-3 is located near the eastern upturned edge of the Rome formation and the lithology suggests that this formation (75 per cent mudrock and shale [29]) may be lighter than the adjacent Tomstown and Elbrook dolomites. Unfortunately no density-determinations are available.

Another conclusion that can be drawn from the absence of local gravity-anomalies is that either the basement-rocks are not involved in the faults and folds observed at the surface or the density-contrast between basement and sedimentary rocks is very small. Magnetic results have been interpreted by Straley [9] to support the former alternative, but density-measurements on crystalline rocks in the Piedmont, reported by Woollard [14], together with the apparent correctness of the assumed density 2.67 for the visible sedimentary rocks in the reduction of the gravity-stations, seem to support the latter alternative. The possibility that a higher density in the pre-Cambrian rocks is compensated by a low-density member in the Cambrian section cannot be ruled out but does not seem to be supported by the shape of the gravity-curves at the eastern end of the profile. Another possibility is that the pre-Cambrian crystallines are denser than the Paleozoic sediments and that the crystalline rock at the Blue Ridge is wedge-shaped and has overridden the Paleozoic sediments to a distance of some miles. Woollard [14] has suggested this condition as a possible explanation for the lack of agreement in geographical positions of the Blue Ridge regional gravity-low and the apparent Appalachian geosyncline. More information on the geological conditions and especially on the rock-densities are required to discriminate between these various possibilities.

In any event, the almost complete absence of gravity-expression of the Paleozoic and perhaps pre-Cambrian rocks, unavoidably leads to the conclusion that the major source of the Appalachian gravity-features must be in the deep basement-rocks either due to upwarps and downwarps or to horizontal lithologic and density-changes. Apparent correlations between seismic velocities and gravity-anomalies have been ascribed to the latter in the Atlantic Coastal Plain [14,15,17] but apparently with only partial success [8]. On the other hand, Ross Gunn [30] has developed a theory of mountain building in which downwarps are associated with horizontal thrusts and Elkins [31] has shown that this theory is in quantitative agreement with the dimensions of the Appalachian Mountains. Gunn's theory indicates that the ordinary concept of isostatic equilibrium will not yield small or zero isostatic gravity-anomalies if vertical stresses are present. Hence, if we interpret the large isostatic anomalies, such as the Blue Ridge low, in terms of Gunn's theory, it would appear that the tectonic forces which produced the Appalachian Mountains are still present.

As a general conclusion it would seem that the present detailed gravimeter-results have not simplified the problem of geophysically unravelling the geologic secrets of Appalachian structure. Rather, the factors have been pushed deeper into the unknown of the Earth's crust. Seismic and perhaps magnetic data would seem to be a necessary adjunct in attempting to solve the problem of the mechanics of the formation of the Appalachian Mountains.

Acknowledgments--The authors wish to express their appreciation to S. S. Sessions who operated the gravimeter in obtaining these data, to W. L. Dowler who traced the illustrations in this paper, and to F. W. Cordwell, D. A. Dander, C. F. Knoderer, G. A. Osborne, J. L. Robinson, Jr., T. H. Tyson, and D. M. Weber who assisted in the station-reductions. Also thanks are due to Dr. Paul D. Foote and Dr. E. A. Eckhardt of the Gulf Research and Development Company and to Dr. Paul H. Price of the West Virginia Geological Survey for permission to publish this paper.

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BARCO GEODETIC SURVEY, SANTANDER DEL NORTE, COLOMBIA, SOUTH AMERICA

Floyd W. Hough
(Abstract by Charles A. Whitten)

[This paper is an abstract of a "Final report on geodetic surveys of the Barco Concession" transmitted to the Colombian Petroleum Company, a subsidiary of the Texas Company, by Floyd W. Hough, Geodetic Engineer. The Section of Geodesy is very grateful to the Texas Company and Mr. Hough for making the report available for this abstract.]

Project--The Barco Concession of the Colombian Petroleum Company is located near the international boundary of Colombia and Venezuela. The purpose of the geodetic survey of this concession was to furnish adequate control for the lot-surveys required. The boundaries of the lots had to be determined with relationship to the international boundary which had been established by an earlier survey. The boundary had been monumented and astronomical observations had been made at some of the monuments, but no adequate geodetic control was available.

Personnel--The field-work was begun in November, 1939, by Commander H. A. Seran, retired. Commander Seran was relieved in June, 1940, by Floyd W. Hough as Chief of Geodetic Surveys. Mr. Hough remained in charge until all of the field-work and most of the office computations were completed. There were three additional engineers in the party and a variable number of laborers ranging from 25 to a maximum of 50 men.

Instrumental equipment--A new Bamberg astronomical transit and the necessary auxiliary equipment were furnished for the astronomical observations. The party was handicapped by not having a modern first-order theodolite. The party used a Kern nine-inch direction theodolite. This instrument gave excellent second-order results but with a more modern instrument, first-order results probably could have been attained without any additional expense. Electric signal-lamps similar to those of the United States Coast and Geodetic Survey were used. Invar tapes were used for the measurement of base-lines and traverses. The equipment included a small Kern micrometer-level, metric level-rods with invar strips, engineer's transit, stretcher-apparatus, spring-balance, 15-kilogram testing weight, and other standard instruments used for the measurement of a base or a traverse line.

Reconnaissance and marking of stations--Because of the lack of maps and the nature of the topography of the country, the reconnaissance presented a difficult problem. An aerial reconnaissance was followed by a ground-reconnaissance. The former was very helpful in the selection of station-sites. Stations were selected with consideration for their adaptability for control, accessibility, economy, and safety of operation. The scheme covered an area of more than 1,000 square miles and consisted of 32 triangulation-stations. The stations were marked with both surface- and underground-marks. The necessary building of tripods and clearing of trees were done as a part of the reconnaissance.

Observations--Horizontal directions were observed with second-order accuracy. The average triangle-closure of all triangles was 1".38. Reciprocal vertical angles were observed over all lines, a mean elevation for each monument being determined from the separate results of the trigonometric leveling. The bases and traverse-lines were measured with high second-order accuracy, the invar tapes being standardized at the National Bureau of Standards in Washington after the completion of the work. The astronomical observations were also of high second-order accuracy, some of them having first-order accuracy.

Observing conditions--The terrain, weather, and natives all worked together to hinder the progress of the survey. The terrain was such that the means of transportation varied considerably, including travel by foot, mule, canoe, launch, automobile, railroad, and aeroplane. Supplies were furnished the remote camps twice each week by mule-train. At two unoccupied stations very high pipe-signals were necessary to clear the trees. One signal was 203 feet high and the other 175 feet. These signals were erected by using 20-foot sections of 3-inch iron pipe. A portion of the signal was raised to a vertical position and then elevated and the extra lengths added at the bottom. Guys of 1/2-inch steel cable kept the signals in place during the erection and then were secured to hold the signals in a permanent position. A cross-arm with pulley at the top of the signal served as a support for a gaoline lantern which was raised and lowered as needed.

The work had to be planned very carefully so as to complete the observations before the rainy season started. After October 1 there was considerable delay because of rain, fog, mud, and washed-out bridges. The natives were so hostile that armed guards were required for protection. The Indians made numerous attacks in which arrows were shot, during one of which a chainman was killed by an arrow and several others wounded. Ten arrows were taken from the carcass of a supply mule which was killed during one of the attacks. Because of these hazards the men in the party received increased compensation.

Computations and datums--The triangulation was adjusted using the least-squares method. There were 30 equations and 82 unknowns. The base-to-base discrepancy after angle- and side-conditions had been satisfied was one part in 142,000. This is excellent agreement considering that the required closure for first-order work in the United States is one part in 25,000. The geographic positions were computed on the International Ellipsoid. Plane coordinates were also computed for all main-scheme stations. The horizontal datum was determined by shifting the triangulation to a position such that the sum of the "A - G's" at five well-spaced astronomical stations would be zero. Even though the relative deflections of the vertical are rather large, the datum seems well determined. The vertical datum is defined as "approximate sea-level."

Recommendations--Among his suggestions for future work, Mr. Hough included an excellent recommendation for the use of small radio telephone-sets known as transceivers. In any country where communication and transportation are difficult, these sets would increase the efficiency of the party. Since Mr. Hough has used such equipment on other projects and is familiar with its use, this recommendation should be given careful consideration.

U. S. Coast and Geodetic Survey,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30 – MAY 3, 1941

SECTION OF SEISMOLOGY

REPORTS AND PAPERS

WASHINGTON, D. C.
MAY 2, 1941

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REPORTS AND PAPERS, SECTION OF SEISMOLOGY
NATIONAL ACADEMY AND RESEARCH COUNCIL BUILDING
2:00 P.M., MAY 1, 1941

SEISMOLOGY IN THE UNITED STATES--A RETROSPECT

James B. Macelwane

(Address of retiring President of Section)

Twenty years ago the total number of seismographic stations in the United States was only a fraction of those we have today. There was not a single first-class station in continental United States. Even the number of second-class stations was very small. Nearly all the stations were third-class from every point of view--equipment, time-service, and personnel. Even among these many were comparatively inactive; some were not even operating.

The Government stations in those days were divided into three groups. To the first group belonged those stations which were under the administration of the Weather Bureau. This was the Bureau officially responsible for seismology in the United States. It published station bulletins in the Monthly Weather Review. The principal stations in this group were Washington, D. C., Northfield, Vermont, and the cooperative station at the University of Chicago. Secondly, there was the station at Balboa Heights under the Canal Zone administration. The third group was maintained by the United States Coast and Geodetic Survey as an incidental activity and was particularly helpful in the interpretation of magnetograph-records. The stations belonging to this group were located at Cheltenham, Tucson, Sitka, Honolulu, and Vieques (near Puerto Rico). Their equipment consisted for the most part of very low-sensitivity horizontal pendulums of the Bosch type.

Of the stations in private institutions we may distinguish several categories. First, there were a few older stations which dated back to the end of the last century or earlier, but which had developed to some extent and had placed somewhat better equipment in operation; such were the stations of the University of California at Berkeley and Lick Observatory which had been founded in 1885 and in 1887, respectively. The rest of the stations with antiquated equipment were only operating spasmodically or had been discontinued altogether. Next there were stations which had good third-class equipment such as the Bosch-Omori pendulums and the small Wiechert seismographs, many of which were not operating regularly because of lack of personnel. Among these were the stations at Ann Arbor, Cambridge, Ithaca, Lawrence, New Haven, Salt Lake City, and Seattle. Finally there was the group of stations which had been established at 15 Jesuit colleges and universities in the years 1909-11 through the initiative of Father Frederick L. Odenbach of Cleveland. Of these stations, very few had operated continuously and still fewer had published a continuous series of bulletins. Among those that had remained continuously active we may mention Denver under Father A. W. Forstall, Fordham, Spokane, Santa Clara, Saint Louis, and especially Georgetown under the direction of the late Father Francis A. Tondorf.

In pleasant contrast to this discouraging state of affairs 20 years ago we now have scattered over the country a large number of seismographic stations, many of which are at least second-class and not a few are first-class stations and there is a considerable personnel whose primary interest is seismology. Among the many causes which have led to this development we may mention first the decision of the Carnegie Institution of Washington to embark on a program of seismological research and development in Southern California about 1920 and the appointment of the Advisory Committee in Seismology under the chairmanship of Dr. Arthur L. Day; secondly, the transfer of official responsibilities for governmental seismology from the United States Weather Bureau to the United States Coast and Geodetic Survey under the able supervision of Captain N. H. Heck in 1924; thirdly, the organization of the Jesuit Seismological Association in 1925.

For purposes of mapping we may define a first-class station as one which has modern highly sensitive seismographs for the measurement of all three components of earth-motion, preferably in two ranges of frequency, trained personnel in charge, a time-service which permits automatic recording of radio time-signals superposed on time-marks made by good clocks, and a sufficiently open time-scale on the recording drums to permit full utilization of these facilities.

We may designate as a second-class station one which is equipped with modern, highly sensitive seismographs but for the horizontal components only and which has personnel and time-service comparable with that required for first-class stations. The third class would include all stations worthy of the name which, for any reason, could not qualify for either of the two previous classes.

When the stations at present in existence in the United States are mapped according to this classification we see that there are three areas that are fairly well covered, namely, the southwestern, northeastern, and central parts of the United States. Large areas in the great plains and eastern mountain region and in the southern and southeastern States remain blank or have at most a third-class station. We hope that the process of transformation of the station at Spring Hill into a second-class station will not be retarded by the serious injuries sustained in an automobile accident by its director, Father Westland, the Chairman of the Eastern Section of the Seismological Society of America.

During the past 20 years the United States has seen considerable development in the design and construction of seismographs of all kinds. Much credit is due to the Carnegie Institution of Washington for its sustained program of instrumental development in Pasadena. The short-period Wood-Anderson seismograph designed for the observation of local earthquakes was the pioneer and really started a new epoch in seismology. This was followed by the long-period Wood-Anderson seismograph, the Benioff reluctance-type vertical component, the Benioff reluctance-type horizontal, the strain-seismograph, the visible-writing seismograph, and finally the Benioff induction-type seismograph. At Washington the Wenner fluxmeter-type and the McComb-Romberg tilt-compensation seismographs were designed and built. At Saint Louis a seismograph for microseisms was designed for use in a local network to determine the nature, direction of propagation, and velocity of microseisms. The same design was later used for a long-period horizontal-component teleseismic instrument. A very highly sensitive short-period vertical-component seismograph was designed and built; but it could not be used in Saint Louis because of traffic disturbances. A simple vertical instrument of low cost was designed by William Sprengnether, Jr., and has proved to be very satisfactory.

For strong-motion work seismometers of several types have been designed. A displacement-meter was designed and built by the late Arthur J. Weed of the University of Virginia. A torsion-type vibration-meter for the measurement of accelerations in a destructive earthquake was designed by Wenner of the National Bureau of Standards. A horizontal vibrometer of high sensitivity was constructed by McComb and Robison and a vertical component by Patterson, Neumann, and Labarre, all of the United States Coast and Geodetic Survey. Reluctance-type vibration-meters were designed by Benioff and built in Pasadena. Very effective vibrators to set buildings

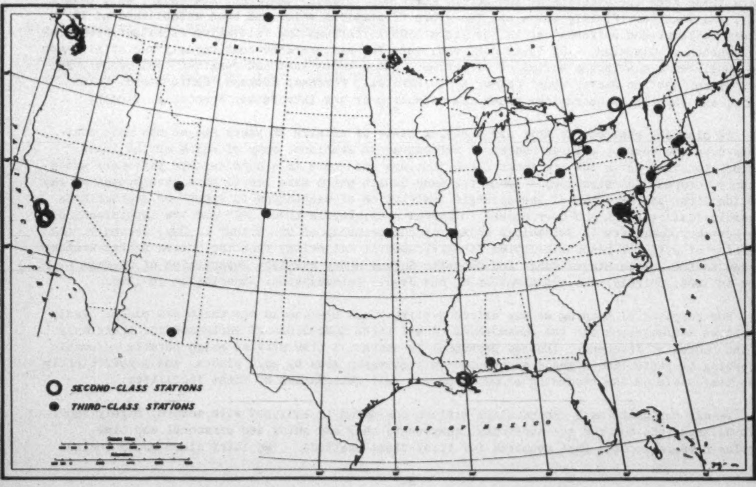

Fig. 1--Seismographic stations in United States, 1921

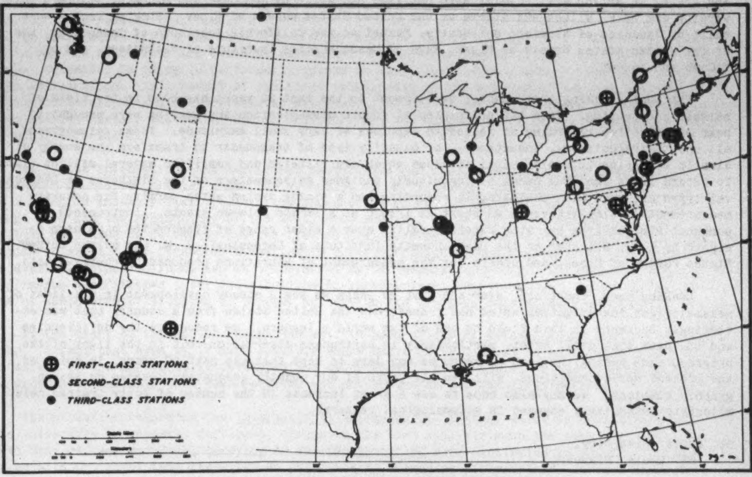
⊕ FIRST-CLASS STATIONS
○ SECOND-CLASS STATIONS
● THIRD-CLASS STATIONS
GULF OF MEXICO

Fig. 2--Seismographic stations in United States, 1941

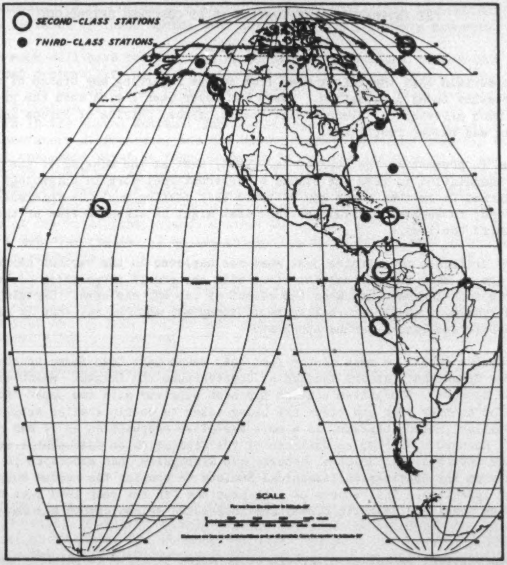
○ SECOND-CLASS STATIONS
● THIRD-CLASS STATIONS
SCALE

Fig. 3--Outlying United States or cooperating seismographic stations

and ground in motion artificially were designed and built by Jacobsen and Blume of Stanford University and by F. W. Lee and others of the United States Bureau of Mines. Shaking tables were built by Jacobsen of Stanford University, Martel of the California Institute of Technology, Lee of the United States Bureau of Mines, Ruge of Massachusetts Institute of Technology, and by McComb and Wenner.

The most striking instrumental development in the last 20 years has been in the field of seismic prospecting. Here the principles of modern communication-engineering were brought to bear on selective recording of reflected impulses of very small magnitude. These seismographs all use the reluctance-, inductance-, or capacity-type of transducer to transform the energy of elastic vibration into electrical impulses which are filtered and amplified several million times. To record these impulses banks of ingeniously designed galvanometers of the Einthoven or D'Arsonval types are used with photographic recording and a timing system which permits the accurate measurement of time-intervals as short as 1/1000 of a second between events. Instruments of somewhat similar type but with record fidelity over a wider range of frequencies have been designed by L. B. Slichter of the Massachusetts Institute of Technology, F. W. Lee of the United States Bureau of Mines, and others for the measurement of vibrations produced by quarry-blasts.

Looking back, therefore, over the last 20 years we see a steady development in all lines of seismological investigation which has transformed the United States from a country that was exceedingly backward in this field to one of the world's leaders. We recognize the deficiencies and the gaps that still exist, particularly in earthquake-observation; but in the light of the progress made during the last 20 years we may dare to hope that the next 20 years, in spite of the present world conditions, will see all parts of our country adequately covered by seismographic stations. We may also hope to see a great increase in the number of fully trained seismologists intensively engaged in seismological research.

St. Louis University,
St. Louis, Missouri

THE INTERNATIONAL SITUATION AS IT CONCERNS SEISMOLOGY

N. H. Heck

It is not certain that the latest news from Europe regarding any branch of scientific work correctly represents today's situation. There has never been a time when the progress in seismology was so much affected by international events, since, outside of Europe and Japan, the program in 1914 was rather restricted.

My purpose in presenting the subject is, first, that at the meeting of the International Seismological Association in 1939 the status of international work in seismology was emphasized and it has occurred to me that those who attended that meeting would be interested in developments; and second, to suggest possible actions that might be taken in view of the international events to minimize the loss.

It is very difficult to appraise just what has happened to the various seismological stations. There are so many things that interfere with the prompt preparation of instrumental reports that it is hard to know just what the effect of the war has been. Certainly, reports are being received from many countries--belligerent, occupied, and neutral--but it will be at least another year before the losses can be appraised.

Special mention should be made of the fact that means have been found to continue the operation of the two Greenland stations located at Scoresbysund and Ivigtut, which are out of communication with Denmark. The latter station has been supplied with the paper (for smoked-paper registration) for another year and steps are being taken to obtain similar supplies for the Scoresbysund station, which, however, is a more expensive proposition as it has photographic recording. Dr. Richard M. Field, as Chairman of the Commission on Continental and Oceanic Structure of the International Union of Geodesy and Geophysics, has succeeded in securing a grant of funds from the American Philosophical Society to provide the needed supplies for another year of operation. The records of both stations for the year 1940 have been loaned to the United States Coast and Geodetic Survey and interested seismologists may have access to this information.

The Bermuda station, established through cooperative activity in which a number of members of the American Geophysical Union took part, is continuing to function with the United States

Coast and Geodetic Survey interpreting the records. The Spanish stations, after a period of inactivity, have resumed their issue of reports. The station at Kingston, Jamaica, established through cooperative effort has been inspected by Reverend Daniel Linehan, S.J., and is functioning though the conditions are somewhat difficult. It has been announced that the new station at Bogota, Colombia, is going to be formally opened in July, 1941, with a modern vertical seismograph in operation. As a result of relations established at the meeting of the Pan American Institute of Geography and History held at Washington, D. C., in May, 1940, there is close cooperation between Mexico, Guatemala, and El Salvador, and the United States in the exchange of seismological information.

As to the International Seismological Association and its Central Bureau at Clermond-Ferrand in unoccupied France, under the direction of Dr. E. Rothé, the known activities since the Washington Assembly have included the preparation of the Bulletin giving preliminary instrumental data and the Proceedings of the Washington meeting, which have been published. The Bulletin continues to be issued but the list of available European and Asiatic stations for the purpose is small. The financial situation is quite difficult. Funds received in the past are not available since no funds can be transferred by the General Secretary, and finally, many governments have stopped their contributions to international organizations. Whatever the outcome of world events, stopping of present activities and complete readjustment is inevitable.

At the start of the war Dr. Rothé had well in hand a list of seismological stations of the world. I feel that even if it were possible there would be little use in publishing this until the effect of the war is fully developed and ascertained. A few copies of the Proceedings of the Washington Assembly have been received but not enough as yet for distribution.

The situation regarding the International Seismological Summary which is published at Oxford University is somewhat different, though in the last analysis much the same. At last reports Miss Bellamy was still carrying on and the Summaries were continuing to appear. It was agreed with Dr. Rothé that there was no objection to Brigadier Winterbotham, General Secretary of the International Union of Geodesy and Geophysics, paying one-half of any funds available for the Seismological Association to Professor Plaskett at Oxford University to continue the work of the Summary, such a division of funds having been adopted at the Stockholm Assembly.

Eventually the work will have to stop, and my purpose in presenting the subject is to call attention to the great desirability of filling the gap when it occurs. There is no desire on the part of anyone in the United States to take over any of this work which has been so well done but there is a situation to be met. There are several agencies engaged in determination of earthquake-epicenters in the United States: The Jesuit Seismological Association at St. Louis; the Seismological Laboratory at Pasadena; and the United States Coast and Geodetic Survey. Is it not possible that the means might be found by which these organizations could get together in some program that would result in the publication of instrumental data for the principal earthquakes? The determinations should be based on all available records and not on those of limited groups of stations. It might also be desirable for other groups to follow the plan of the Manila Central Observatory of the Philippine Islands Weather Bureau and give determinations for principal earthquakes of a definite region. I am not attempting to solve the problem but merely to call attention to the situation.

Whatever temporary measures are taken, including discontinuance of activity on account of loss of funds, the International Seismological Association will not be dead. The old Association came to a technical end in 1914, but it was replaced by a more effective organization, so the future can be faced without pessimism.

United States Coast and Geodetic Survey,
Washington, D. C.

PROGRESS-REPORT, CANADIAN SEISMOLOGICAL STATIONS

W. W. Doxsee

Owing to war conditions very little has been accomplished during the last year in the field of improvements to service. A noteworthy advance has been made in the matter of securing a suitable light-source of standard type at moderate cost. The photo-cell exciter lamp has proved entirely satisfactory for use with seismographs of the Milne-Shaw and Wood-Anderson types. To date it has not been possible to secure a standard socket for use with these lamps, necessitating the design and construction of special sockets, each suited for use with the lantern in which it is to be installed. The types of this lamp are all of short-filament construction, variation being provided in the matter of different voltages and amperage. Up to the present only those of 8.5 and 10 volts have been tried; both types have operated with equally satisfactory results. At the Quebec stations, where two 6-volt batteries in series are the power-source, the 10-volt type is giving ample light-energy for good registration at the 60-mm per minute drum-rotation speed of the Wood-Anderson recorder. This, too, is obtained with a current-consumption of a little more than half of the five-ampere rating, this prolonging the life of the lamp--a factor both in point of service and in maintenance upkeep. Another important factor is that the filament is in a fixed distance-relationship to the base-contact points so that once the optimum setting of the socket has been determined, lamp-replacements can be made without requiring any lantern-adjustment to secure continued uniformity of registration quality. The 8.5-volt type is now in use with one of the Milne-Shaws at Ottawa, current-supply being from step-down transformer fed from the 110-volt alternating lighting circuit. This same type is battery-operated at Kirkland Lake with the Heiland recorder. At both Ottawa and Kirkland Lake the results are entirely satisfactory. It is probable, however, that the 10-volt type will be adopted at all stations as a matter of standardizing servicing equipment. As conditions permit the Milne-Shaws at Victoria and Toronto, the Bosch at Halifax, and the other Milne-Shaw component at Ottawa will be equipped to use exciter-lamps as a light-source. The Benioff recorders as supplied by the manufacturers are already equipped to use a standard commercial lamp of the auto type, so that no advantage would accrue from a change-over to the exciter-type other than a possible gain in the length of lamp-life.

Staff reduction due to the enlistment of M. J. S. Innes in the Royal Canadian Air Force has resulted in the indefinite postponement of a number of planned activities.

Even the regular routine of interpreting the seismograms from the stations of the Canadian network would have been curtailed had it not been possible to arrange for part-time service of a member from another Division of the Observatory. Miss M. S. Burland continues to carry a limited part of her program with the 15-inch telescope but for the duration of the war is giving the greater part of her time to the work of the Seismological Division. We have thus been able to carry without interruption the regular routine, monthly bulletins, and reports dealing with seismic registrations in Canada.

Dominion Observatory,
Ottawa, Canada

THE SPRENGNETHER VERTICAL SEISMOGRAPH

James B. Macelwane and W. F. Sprengnether, Jr.

William Sprengnether, Jr., of the Sprengnether Instrument Company in Saint Louis, Missouri, has designed an instrument to supply the apparent demand for a simple, low-priced, short-period, vertical-component seismograph of fairly high sensitivity. The frame consists of a rigid truss with a long hinge-bar at right-angles to it. Above the rear end of the truss a weight is carried by a vertical bar on which it is adjustable in order to regulate the period by setting the center of gravity in any desired relationship to the point of suspension from the spiral spring. The principal part of the mass consists of this counterweight and of a brass box at the forward end of the truss containing a pair of elliptical brass spools on which are wound flat coils; and to a lesser extent a copper plate supported on a forward extension of the boom or truss adds to the inertia-mass of the moving system. The hinge consists of two pairs of thin crossed springs attached to the hinge-bar of the moving system and to a rigid cross-piece fastened to the frame. The coil-box is free to move between the poles of a large, powerful Alnico magnet. The copper plate moves between the poles of three pairs of commercial Alnico horseshoe magnets by which critical damping is easily obtained. Wires are led from the coil-box over the frame to the neighborhood of the hinge-line and thence to a galvanometer. The period chosen in the case of the instrument with which we have been working at Saint Louis University lies between the microseisms which usually have periods from four to seven seconds and the local traffic disturbances which have periods less than a second.

The seismometer has been in operation since mid-winter and has given us excellent satisfaction. We have not had the opportunity as yet to make an accurate determination of the constants but our estimate of the overall synchronous magnification of the combination we are using, is about 3,000. It seems to us that an instrument of this type is badly needed. There are many stations which have no vertical component and whose finances will not permit the purchase of more elaborate equipment. Our experience convinces us that it will not only produce good records of local earthquakes but that it will react to the shorter periods in the beginning of distant earthquakes to such an extent as to produce a sharp record of the beginning where horizontal seismographs of moderately high sensitivity will fail to do so. In the recent Mexican earthquakes, for example, the motion in the P-phase of the main shock was so rapid and so large that even the turning point often failed to record; but the first throw is a sharp impulse downward indicating a condensation. A little over a half-hour later the P-phase of the first aftershock

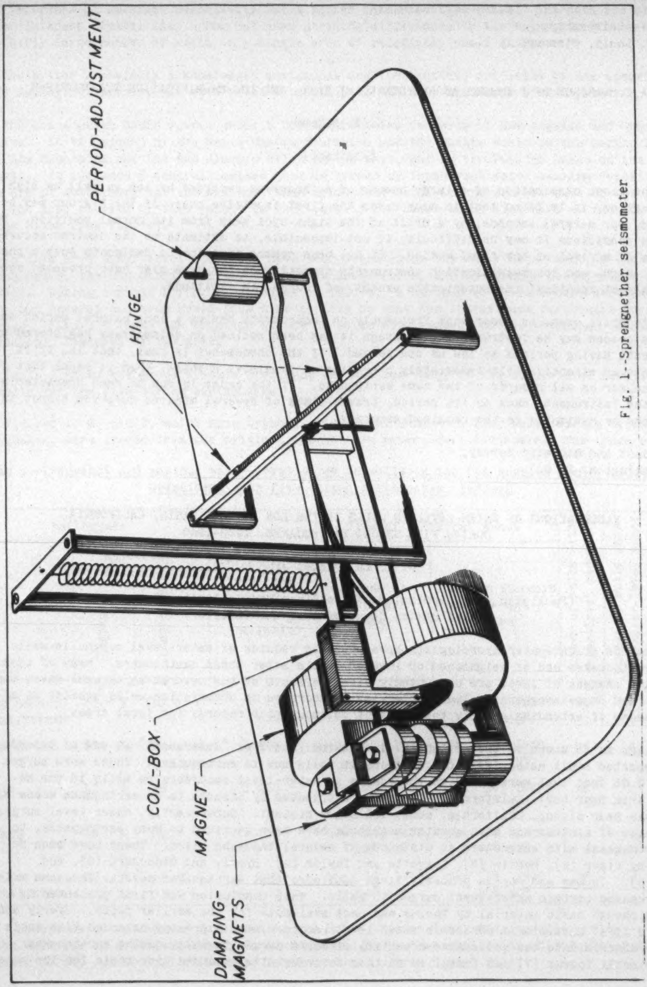

Fig. 1--Sprengnether seismometer

is recorded with large amplitudes beginning with a sharp rarefaction. This aftershock could not be distinguished on any of the records of long-period horizontal seismographs because of the violent motion which was still going on. Two other aftershocks of considerable energy besides several minor ones were recorded in the course of a few hours. In each of these cases the beginning of the vertical record is very sharp and shows the double phase which indicates a depth of about 100 km at the distance of the Mexican earthquakes. In every case except that of the main shock the first impulse is a rarefaction.

St. Louis University,
St. Louis, Missouri

A COMPARISON OF P-PHASES AS REGISTERED BY HIGH- AND LOW-MAGNIFICATION SEISMOGRAPHS

H. E. McComb

(Abstract)

Upon close examination of a large number of seismograms recorded by low as well as high magnification, it is found that in many cases the first impulsive phase of the P-group may be preceded, for several seconds, by a drift of the light-spot away from its normal position. Under such conditions it may be difficult, if not impossible, to estimate to the desired accuracy the time of arrival of the first motion. It has been common practice to designate such a phase as "e". High- and low-magnification instruments operating on the same pier have produced records having almost identical characteristics except, of course, in amplitude.

This drift seems to occur most frequently on instruments having a long natural period and for this reason may be instrumental, although it has been noticed on seismograms registered by instruments having periods as low as one second. If the phenomenon is real, that is, if it represents an effective tilt immediately preceding an impulsive P-phase, then it seems that it should appear on all records of the same earthquake. If the cause is due to some characteristic of the instrument, such as its period, travel-times of several minutes duration cannot in such cases be estimated to the required accuracy.

U. S. Coast and Geodetic Survey,
Washington, D. C.

FLUCTUATIONS OF WATER-LEVEL IN WELLS IN THE LOS ANGELES BASIN, CALIFORNIA, DURING FIVE STRONG EARTHQUAKES, 1933-1940

G. A. La Rocque, Jr.*

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United States Department of the Interior)

Numerous ground-water hydrologists have obtained records of water-level surges in wells during earthquakes and of heightened or lowered levels after those earthquakes. Many of these surges and changes of level are undoubtedly direct effects of the several earthquake-waves that are recorded on seismographs. Thus, water-level recorders on observation-wells promise to afford a means of extending greatly the scope of seismographic records for local areas.

So far as is known to the writer, H. T. Stearns [see 1 of "References" at end of paper] first reported small water-level fluctuations in wells due to earthquakes. These were surges of 0.02 to 0.05 foot that were shown on the charts of water-level recorders on wells in the Mokelumne Area near Lodi, California. They were attributed by Stearns to an earthquake whose epicenter was near Bishop, California, about 150 miles distant. Subsequently, water-level surges and changes of similar and much greater magnitude have been ascribed to many earthquakes, to some earthquakes with epicenters at distances of several thousand miles. These have been described by Piper [2], Morris [3], Leggette and Taylor [4], Byerly and Blanchard [5], and Thomas [6]. Thomas and Morris probably first concluded that earthquakes several thousand miles distant caused certain water-level surges in wells. This conclusion was first presented by Morris although basic material by Thomas was made available for the earlier paper. Byerly and Blanchard first assembled a sensitive water-level recorder with a greatly extended time-scale in order to discriminate the successive momentary pressure-surges in wells during earthquakes. Quite recently Thomas [7] has installed another recorder with extended time-scale for the same purpose. Most of the published material just cited and a considerable amount of recent unpublished data have been summarized by Thompson [8].

This brief report describes short-term surges of water-level in wells in the eastern part of the Los Angeles Basin, California, about coincident in time with, and inferentially caused mainly by, five strong earthquakes that occurred between 1933 and 1940 at widely separated places on the Earth. These surges occurred in observation-wells that were equipped with water-level recorders of moderate sensitivity but a rather condensed time-scale. The data are of particular interest because they bring out some striking differences in the magnitude of the surge in a fairly large number of wells in a single area of relatively small extent.

The writer gratefully acknowledges assistance and constructive criticism by his associates in the Geological Survey, who have added materially to the original scope of the paper.

The Los Angeles Basin covers about 1,000 square miles in parts of Los Angeles and Orange counties. It is bounded by the Santa Monica Mountains and the Puente Hills on the north, by the Santa Ana Mountains and the San Joaquin Hills on the east, and by the Pacific Ocean on the south and west. It includes a central lowland that is formed by incoherent water-bearing deposits which are of Quaternary age and are more than 1,600 feet thick in the central part of the basin [9]. The area covered by this report is that part of the basin which lies east of the Los Angeles River [see Fig. 4].

In this area water-level recorders have been operated by the water department of the City of Long Beach, the San Gabriel Valley Protective Association, and the Orange County Flood Control District. During several strong earthquakes of 1933-40, a maximum of 26 recorders were in operation, but several had been moved from time to time so that the charts show earthquake surges in 35 wells. Figure 4 shows the location of the 35 wells with respect to the principal topographic and geologic features of the area.

Table 1 shows the proportionate frequency and maximum range of the water-level surges in the wells for the five strong earthquakes.

Figures 1, 2, and 3, which show typical water-level surges in four wells during certain earthquakes, were traced from the original charts from water-level recorders. The trace of the

Table 1--Frequency and maximum water-level surge in wells in the Los Angeles Basin, California, coincident with five strong earthquakes, 1933-40

Earthquake			Distance of epicenter from Long Beach (statute miles)[b]	Time of principal shock		Number of wells with water-level recorders	Number of wells showing water-level surge	Greatest surge, in feet
Area	Epicenter[a]			Greenwich date and time	Western standard date and time			
	Latitude	Longitude						
Long Beach, California	33.6° N	118.0° W	17[c]	Mar. 11, 1933, $01^h\ 55^m$	Mar. 10, 1933, $17^h\ 55^m$	26	26	10.58
Alaska	56 N	159 W	2,490	Nov. 10, 1938, $20^h\ 18^m$	Nov. 10, 1938, $12^h\ 18^m$	24	16	0.85
Chile	37 S	73 W	5,680	Jan. 25, 1939, $03^h\ 32^m$	Jan. 24, 1939, $19^h\ 32^m$	25	0	....
Turkey	39 N	39 E	7,200	Dec. 26, 1939, $23^h\ 57^m$	Dec. 26, 1939, $15^h\ 57^m$	24	2	0.045
El Centro, California	32 N	115.45 W	175	May 19, 1940, $04^h\ 36^m$	May 18, 1940 $20^h\ 36^m$	25	13	1.26

[a] Locations of epicenters furnished by the United States Coast and Geodetic Survey. [b] Distances measured on a large globe by R. R. Bodle and D. G. Thompson of the United States Coast and Geodetic Survey and Geological Survey, respectively. [c] From Signal Hill.

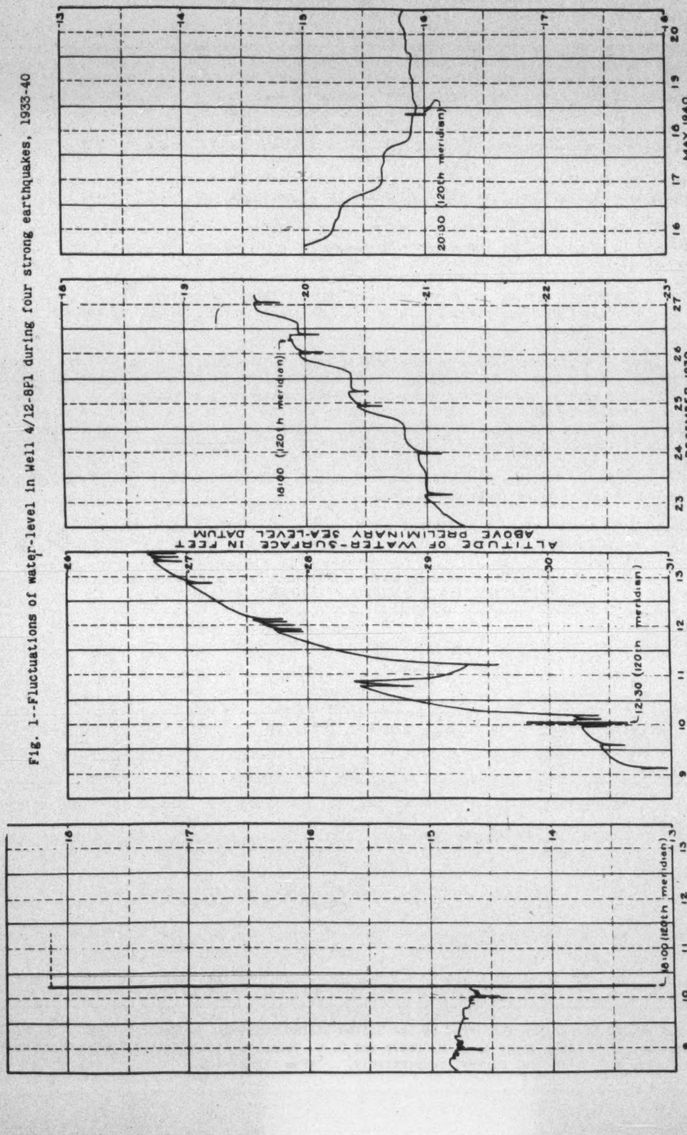
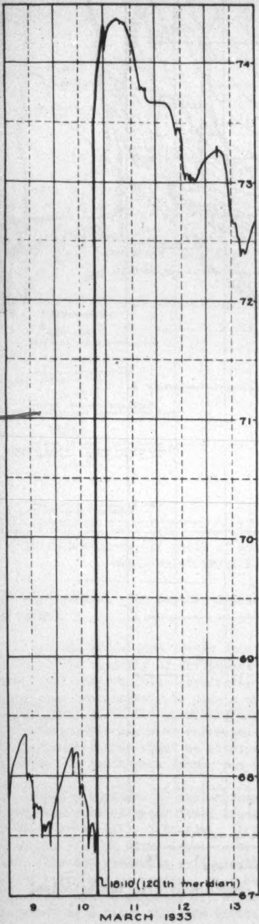


Fig. 1--Fluctuations of water-level in Well 4/12-8P1 during four strong earthquakes, 1933-40 earthquake surge is accentuated in these Figures; on the original charts this trace was no wider than normal.

It is believed that the abnormal surges of water-level shown by the preceding three Figures were caused largely by the respective earthquakes. However, certain parts of the surges in wells 3/12-8L3 and 5/10-9R2 during the Long Beach earthquake probably were not so caused. Thus, the uppermost foot of the surge in Well 3/12-8L3, from about altitude 73.3 feet to the maximum at about 74.3 feet, probably was due to stoppage of pumps in other wells nearby. In Well 5/10-9R2, likewise, the earthquake surge probably merges into the diurnal fluctuation which is the characteristic effect of withdrawals from nearby wells. Typical diurnal fluctuations of this sort are shown on the Figure just before and after the major surge. In the graphs for wells 5/10-9R2 and 4/12-28H10 the trace of the major surge is broken and offset in time. The most likely explanations are that the pencil of the recorder was displaced by the earthquake-shock or that the float was entangled temporarily.

On preceding Figures the chart-time for water-level surges during the Long Beach earthquake ranges from 17:30 to 18:10 o'clock (120th meridian time), whereas the principal earthquake-shock occurred at 17:55 o'clock. It is believed that the range in chart-time is due largely to incorrect travel of the recording pencils and that the



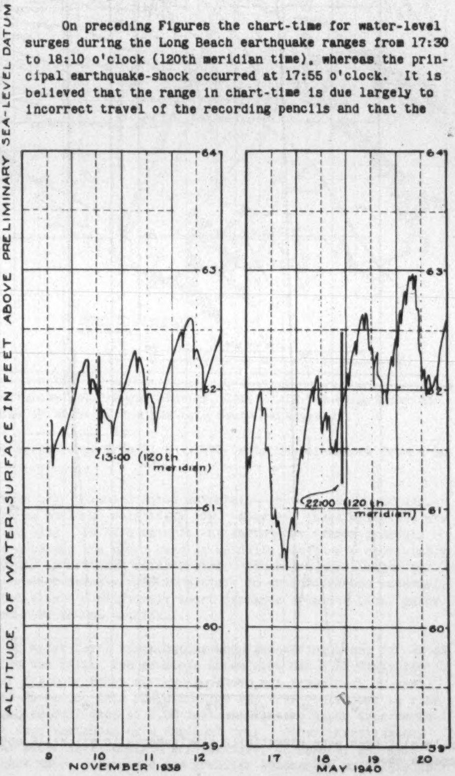
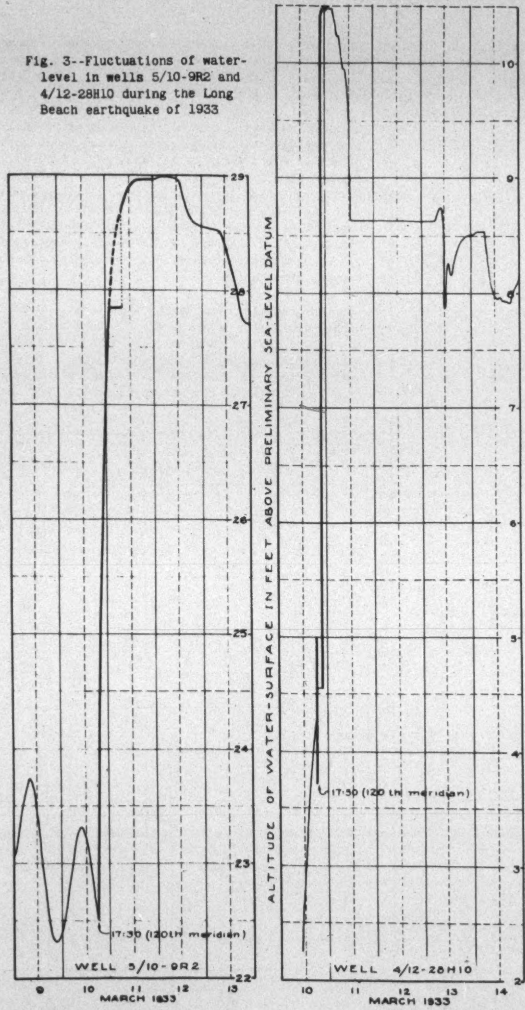


Fig. 2--Fluctuations of water-level in Well 3/12-8L3 during three strong earthquakes, 1933-40

Fig. 3--Fluctuations of water-level in wells 5/10-9R2 and 4/12-28H10 during the Long Beach earthquake of 1933



water-level surges were essentially simultaneous in all wells and synchronous with the principal earthquake shock.

Table 2 describes the wells on which water-level recorders were in operation during the five earthquakes and shows the magnitude of the water-level surge in each well during each of

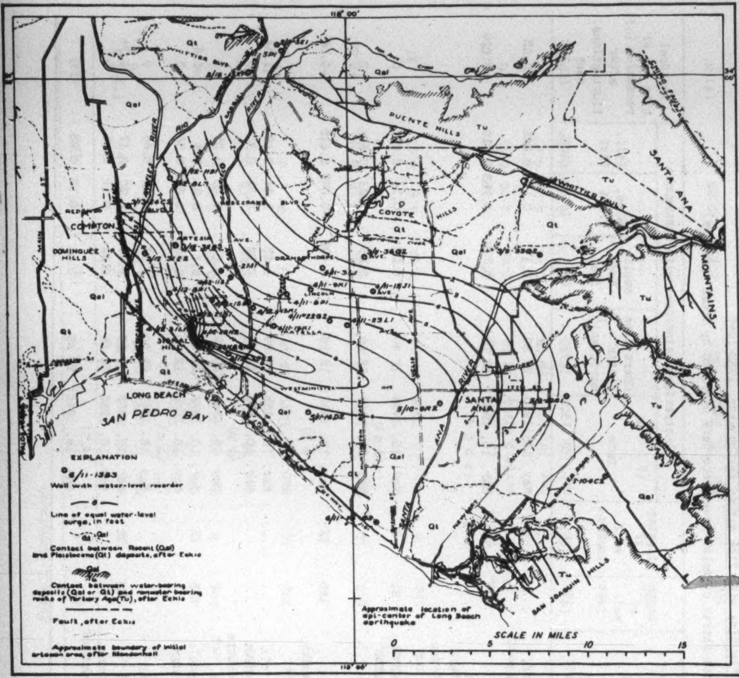

118° 00'
Qt
Qal
WHITTIER BLVD
PUENTE HILLS
Tu
SANTA ANA
WHITTIER FAULT
COYOTE HILLS
COMPTON
DOMINGUEZ HILLS
SIGNAL HILL
LONG BEACH
SAN PEDRO BAY
SANTA ANA
SANTA ANA RIVER
MOUNTAINS
SAN JOAQUIN HILLS
EXPLANATION
6/11-1383
Well with water-level recorder
Line of equal water-level surge, in feet
Contact between Recent (Qal) and Pleistocene (Qt) deposits, after Eckis
Contact between water-bearing deposits (Qal or Qt) and nonwater-bearing rocks of Tertiary Age (Tu), after Eckis
Fault, after Eckis
Approximate boundary of initial artesian area, after Mendenhall
Approximate location of epi-center of Long Beach earthquake
SCALE IN MILES
0
5
10
15

Fig. 4--Sketch-map of parts of Los Angeles and Orange counties, California, showing lines of equal water-level surge in wells during the Long Beach earthquake

the earthquakes. The depths of these wells range from 81 to 1,570 feet, the diameters from 4 to 26 inches.

All the wells just listed penetrate only unconsolidated materials--gravel, sand, and clay--in which the velocity of earthquake waves would be relatively low. However, these materials are relatively compressible, especially the clay. In such material an earthquake tremor probably would tend successively to dilate and compress the water-bearing conduits, which are appreciably elastic, and so to set up pressure-surges in confined water-bodies. These pressure-surges in the water-bodies would be reflected in water-level surges in wells. In unconsolidated material, the pressure-surges might be dissipated within a relatively short distance from the focal point at which the earthquake tremor was imparted to the material.

Table 2 includes 57 evaluations of water-level surge during the five earthquakes; for 32 of these, the rise of water-level exceeded the fall. The greatest known rise was 8.23 feet; the greatest known fall, 3.61 feet. After the Long Beach earthquake there was a residual or semi-permanent rise in water-level in 24 of 25 wells; this residual rise was from 0.019 foot to 8.23 feet. The one remaining well showed a residual drop of 0.06 foot. After the other four earthquakes there was no residual rise but four instances of a residual drop. Other investigators have found that a majority of residual water-level changes are positive, or upward, and have suggested as a cause that the earthquake shock rearranged the granular incoherent materials in which the water occurred. Any such rearrangement of granules would tend to compact the water-

Table 2--Fluctuations of water-level in 35 wells in the Los Angeles Basin, California, about coincident in time with five strong earthquakes, 1933-1940

[Data by U. S. Geol. Survey from charts of water-level recorders operated by local agencies]

No. of well		Local agency and location of well	Depth of well, feet	Diameter of well, inches	Fluctuations coincident with earthquake					Residual rise (+) or recession (-) after fluctuations, feet
Geological Survey (1)	Local agency (2)	(3)	(4)	(5)	Date (6)	Chart time (120th meridian)^1 (7)	Amplitude, feet (8)	Rise, feet (9)	Fall, feet (10)	(11)
2/11-5E1	396t	Temple School, about 0.45 mile west of; about 0.05 mile south of Durfee Road	....	....	May 18, 1940 (a b c)	h m 20 30	0.17	0.105	0.065	-0.03
2/11-5P1	240q	Bartolo, about 0.7 mile west of; in Whittier Narrows, 0.1 mile south of Southern California Edison Company's transmission-line, 0.1 mile west of San Gabriel River	400	10	Mar. 10, 1933 (a b c d)	18 10	0.172	0.153	0.019	+0.019
2/12-13A1	803g	Pico, about 0.5 mile west of, in southeast angle of Lexington Road and Union Pacific Railroad, about 0.05 mile southeast from crossing	81	8	Nov. 10, 1938 (b c)	12 40	0.23	0.14	0.09	0
					May 18, 1940	22 00	0.54	0.23	0.31	0
3/9-33Q2	1082g	Atwood, about 0.4 mile southeast of; about 500 feet north of Walnut Street, 50 feet west of Richfield Road	180	12	Mar. 10, 1933 (a b)	18 10	0.493	0.078	0.415	-0.08
3/11-36Q2	981n	Buena Park, about 0.7 mile southwest of; about 500 feet east of Southern Pacific Railroad, 150 feet north of Orangethorpe Avenue	....	....	Mar. 10, 1933	18 05	1.53	1.34	0.19	+1.34
					Nov. 10, 1938 (b c)	12 30	0.02	0.01	0.01	0
					May 18, 1940	20 45	0.08	0.03	0.05	0
3/12-8L3	872a	Los Angeles County Farm Hospital (Hondo); about 0.35 mile south of Imperial Highway, 0.45 mile west of Paramount Boulevard	285	12	Mar. 10, 1933	18 10	6.1	5.5	0.6	+6.6
					Nov. 10, 1938 (b c)	13 00	0.665	0.300	0.365	0
					May 18, 1940	22 00	1.26	0.61	0.65	0
3/12-11D1	848	Downey, about 1.3 miles southeast of; about 900 feet east of Woodruff Avenue, 20 feet south of Norwalk Road (Firestone Boulevard)	83	12	Mar. 10, 1933	17 50	2.87	2.70	0.17	+0.7+
					Nov. 10, 1938 (b c)	12 45	0.22	0.11	0.11	0
					May 18, 1940	20 45	0.41	0.18	0.23	0

Table 2--Continued

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
						h m				
3/12-31E2	929f	North Long Beach; about 90 feet south of Smith Street, 35 feet west of Linden Avenue	907	12	Mar. 10, 1933	17 55	....	4.23	(e)	(f)+3.6
					Nov. 10, 1938	12 15	0.34			0
					Jan. 24, 1939		(e)			
					Dec. 26, 1939		(e)			
					May 18, 1940		(e)			
3/12-32B3	885d	Hynes, Funderburk well of the city of Long Beach, south side of 65th Street, east of Paramount Boulevard, in rear of fire station	204	8	Nov. 10, 1938 (b c)	15 45	0.23	0.12	0.11	0
					May 18, 1940	20 45	0.24	0.13	0.11	0
3/13-24C2	879c (B-82)	Compton; about 45 feet south of Orange Street (Rosecrans Avenue), 0.2 mile west of Atlantic Avenue, 100 feet east of Butler Avenue	196	10	Mar. 10, 1933	18 15	6+	6+	0	+7.0
4/11-3L1	950k	Buena Park, about 1.5 miles southwest of; about 3,380 feet west of Hansen Street, 2,110 feet south of Orangethorpe Avenue	518	12	Mar. 10, 1933 (a b c d)	18 00	2.21	2.18	0.03	+3.64
4/11-8P1	900	Cypress, about 1 mile west of; about 325 feet north of Lincoln Avenue (Carson Street), 110 feet west of Dennie Road extended	550	4	Mar. 10, 1933	18 00	4.83	4.8	0.03	(g)
4/11-9K1	1006a	Cypress, about 0.3 mile northeast of; about 0.16 mile south and 0.24 mile east of intersection of Walker Street and Crescent Avenue	600+	12	Mar. 10, 1933	18 00	4.23	4.15	0.08	+4.15
					Nov. 10, 1938 (b c)	12 15	0.23	0.09	0.14	0
					May 18, 1940	20 30	0.15	0.08	0.07	0
4/11-12J1	983h	Anaheim, about 3.5 miles west of; about 0.26 mile north of Lincoln Avenue (Carson Street), 200 feet east of Magnolia Avenue	100	10	Mar. 10, 1933	17 30	0.270	0.244	0.026	+0.24
4/11-19K1	909k	Los Alamitos, about 0.5 mile north of; about 70 feet south of Spring Street, 1,250 feet east of Los Alamitos Boulevard	448	12	(a b c d)	.. ..	....	....	....	....
4/11-22G2	927k	Hansen, about 0.35 mile southwest of; about 0.38 mile west of Hansen Street, 0.28 mile south of Ball Road	150	10	Mar. 10, 1933	(h)	6.29	6.29	0	(f)+6

Table 2--Fluctuations of water-level in 35 wells in the Los Angeles Basin, California, about coincident in time with five strong earthquakes, 1933-1940--Continued

No. of well		Local agency and location of well	Depth of well, feet	Diameter of well, inches	Fluctuations coincident with earthquake					Residual rise (+) or recession (-) after fluctuations, feet
Geological Survey (1)	Local agency (2)	(3)	(4)	(5)	Date (6)	Chart time (120th meridian)[1] (7)	Amplitude, feet (8)	Rise, feet (9)	Fall, feet (10)	(11)
						h m				
4/11-23L1	984b	Stanton, about 0.5 mile west and 0.5 mile north of; about 420 feet south of Cerritos Street (Spring Street), 100 feet west of Western Avenue	....	....	Mar. 10, 1933	17 55	(1)6.4+	(1)6.4+	0.02	(1)+6.4+
					Nov. 10, 1938 (b c)	12 35	0.05	0.02	0.03	0
					May 18, 1940	20 45	0.02	0.01	0.01	0
4/12-2M1	901	Bellflower, about 2 miles south of; Montana Land Company Well 45, about 1.4 miles north of Carson Street, 400 feet east of Woodruff Avenue	673	12	Nov. 10, 1938 (b c)	13 30	0.12	0.07	0.05	0
					May 18, 1940	19 30	0.13	0.065	0.065	0
4/12-8P1	926	Long Beach, about 4.8 miles north of; about 140 feet east of Union Pacific Railroad, 2,590 feet north and 1,200 feet east of intersection of Cherry Avenue and Bixby Station Road	714	12	Mar. 10, 1933	18 00	5.1	3.5	1.6	(f)+3
					Nov. 10, 1938 (b)	12 30	0.85	0.43	0.42	0
					Dec. 26, 1939	18 00	0.03	0.03	0	0
					May 18, 1940	20 30	0.18	0.06	0.12	-0.02
4/12-11B2	901c	Bellflower, about 3 miles south of; Montana Land Company Well 42, about 200 feet south of Artesia Avenue and 200 feet east of Palo Verde Avenue	1,075	12	Mar. 10, 1933	18 10	3.5+	3.5+	0.01	+5.06
4/12-13K1	909c	Artesia, about 2.2 miles south of; about 0.64 mile south of Lincoln Avenue (Carson Street), 0.42 mile west of Pioneer Boulevard extended, 0.15 mile east of the San Gabriel River	875	12	Mar. 10, 1933	17 50	6.29	6.29	0	+6
4/12-15B1	908k	Long Beach Water Department, Commission Well 3; 200 feet south of Carson Street, 180 feet east of Somerset Avenue	1,570	26-13	Mar. 10, 1933	17 50	(j)4.58	0.97	3.61	+0.59
4/12-21G1	916d	Long Beach, about 1.5 miles northeast of Signal Hill; about 1,000 feet north of Spring Street, 600 feet east of Cerritos Avenue, about 0.35 mile northeast of Well 4/12-21L1	338.7	10	Mar. 10, 1933	17 50	7.99	6.53	1.46	(g)
					Nov. 10, 1938 (b c d)	12 30	0.03	0	0.03	-0.03

Table 2--Continued

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
						h m				
4/12-21L1	937d	Long Beach Water Department, Citizens Well 4 northeast of Signal Hill; about 0.3 mile east of Newport Avenue, 150 feet south of Spring Street	1,155	12-10	Mar. 10, 1933	17 50	3.74	3.74	0	+3
					Nov. 10, 1938 (b c)	12 15	0.28	0.11	0.17	0
					May 18, 1940	20 45	0.15	0.05	0.10	0
4/12-28H2	938c	Long Beach Water Department, Alamitos Well 5; about 225 feet east of Alamitos Well 1 (4/12-28H9)	994	12	Mar. 10, 1933 (a b c d)	17 50	10.58	8.23	2.35	+8.23
4/12-28H8	938b	Long Beach Water Department, Alamitos Well 2; about 150 feet west of Alamitos Well 1 (4/12-28H9)	273	12	Nov. 10, 1938 (b c)	12 40	0.11	0	0.11	-0.11
					May 18, 1940	20 30	0.089	0.024	0.065	0
4/12-28H9	938a	Long Beach Water Department, Alamitos Well 1 east of Signal Hill; about 0.8 mile east of Newport Avenue, 150 feet north of Stearns Street	745	12	(a b c d)	.. ..	....	....	....	....
4/12-28H10	938e	Long Beach Water Department, Alamitos Well 7; about 1,150 feet N. 21° E. from Alamitos Well 1 (4/12-28H9)	1,114	26-16	Mar. 10, 1933 (b c)	17 50	7.07	6.40	0.67	+6.40
					Nov. 10, 1938	(h)				
4/12-35C2	914	Seal Beach, about 3 miles north of; about 0.25 mile west of Palo Verde Avenue, 0.50 mile south of Bixby School, on Stearns Street	....	10	(a b c d)	.. ..	....	....	....	....
4/13-12G2	9351	North Long Beach; 76 feet east of American Avenue, 245 feet north of Country Club Drive; at Virginia Country Club	1,000	16	Mar. 10, 1933	17 00	1.87	1.87	0	+1.29
					Nov. 10, 1938 (b c d)	12 45	0.005	....	....	0
5/9-10G1	1195b	Santa Ana, about 3.5 miles east of; about 150 feet east of Newport Boulevard, 0.25 mile south of East 17th Street	210	16	Mar. 10, 1933	17 50	0.35	0.17	0.18	0
					Nov. 10, 1938 (b c d)	13 00	Trace	....	....	0
5/10-9R2	1167c	Santa Ana, about 3 miles west of; about 150 feet west of Buaro Street (Fairview Avenue), 50 feet south of West 5th Street	97	7	Mar. 10, 1933	.. ..	0	0	0	(k)+6.45
5/11-16D2	991e	Seal Beach, about 4 miles east of; about 1,600 feet west of Graham Avenue, 600 feet south of Bolsa Street	400+	10	Mar. 10, 1933	17 55	5.33	5.33	0	+5.02
					Nov. 10, 1938	12 30	0.270	0.145	0.125	0
					Dec. 26, 1939 (c)	17 00	0.045	0.030	0.015	0
					May 18, 1940	20 45	0.185	0.075	0.110	0

Table 2--Fluctuations of water-level in 35 wells in the Los Angeles Basin, California, about coincident in time with five strong earthquakes, 1933-1940--Concluded

No. of well		Local agency and location of well	Depth of well, feet	Diameter of well, inches	Fluctuations coincident with earthquake					Residual rise (+) or recession (-) after fluctuations, feet
Geological Survey (1)	Local agency (2)	(3)	(4)	(5)	Date (6)	Chart time (120th meridian)[1] (7)	Amplitude, feet (8)	Rise, feet (9)	Fall, feet (10)	(11)
				h m						
6/11-13B3	1263a	Huntington Beach, about 1 mile east of; about 400 feet east of drainage-ditch along Pennsylvania Avenue, 0.25 mile south of Atlanta Street	154	12	Mar. 10, 1933 (a b c d)	17 55	(i)	(i)	0.77	+1.5+
I-104C2	1222h	Irvine, about 1.4 miles northwest of; about 500 feet west of highway U. S. 101, 0.2 mile northwest of Jeffrey Road	963	15-10	(a b) Dec. 26, 1939 (d)	(h)	....	....	....	....

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[1] Discrepancies between chart-time of water-level surge and time of principal earthquake shock probably due largely to errors in setting and travel of recording pencil.

(a) No abnormal surge during earthquake of November 10, 1938. (b) No abnormal surge during earthquake of January 24, 1939. (c) No abnormal surge during earthquake of December 26, 1939. (d) No abnormal surge during earthquake of May 18, 1940. (e) Abnormal surge, if any occurred, masked by effects of pumping in nearby wells. (f) Estimated. (g) Amount of residual rise or recession not shown. (h) Water-level recorder not operating properly; time or amount of surge, or both, not shown. (i) Height range of water-level recorder insufficient to span the range of water-level during the earthquake. (j) Possibly too small; the diameter of well-casing is only 13 inches where perforated but is 26 inches at water-level. (k) Only water-level fluctuation was a progressive rise, beginning about 17:30 o'clock.

bearing strata and so to diminish the total pore-space. Morris [10] has suggested that a negative residual change in water-level indicates release of stress on the water-bearing zone, with some deformation of the ground-water basin.

As the preceding Table shows, the greatest water-level surge during the Long Beach and Alaskan earthquakes on the one hand and during the El Centro earthquake on the other hand occurred in two distinct groups of wells. The respective groups of wells tap deep bodies of confined water on the one hand, but, on the other hand, shallow bodies of confined water or bodies of water that may not be effectively confined. Also, the respective groups lie toward the epicenters of the Long Beach and El Centro earthquakes. That one distinct group of wells showed the greatest surge during the Long Beach and Alaskan earthquakes (epicentral distances of 17 and 2,490 miles, respectively) suggests that the earthquake waves are resolved and directed locally by faults and other geologic features of the area. This suggestion is further developed beyond.

In the 16 wells at which a water-level recorder was in operation during all five strong earthquakes the amplitude of the water-level surge was, without exception, greatest during the Long Beach earthquake, whose epicenter was closest. For this earthquake, it was possible to sketch lines of equal surge in wells (see Fig. 4). In sketching these lines, the surge in wells 4/12-15B1 and 6/11-13B3 was disregarded because it was not clearly shown by the recorder charts.

The salient two features of Figure 4 are: (1) The greatest known water-level surge in wells during the Long Beach earthquake occurred just northeast of and close to the so-called Inglewood-Newport fault-zone close to Signal Hill but (2) the epicenter of the earthquake was apparently some 15 miles to the southeast, about on the prolongation of the fault-zone and a few miles offshore. Possibly there was an appreciable pressure-surge in bodies of ground-water on the opposite or southwest side of the fault-zone. However, no wells in that area were equipped with water-level recorders at the time so that the magnitude of the amount of surge, if any occurred, is not known.

In and near this area of greatest known water-level surge the impervious beds in the unconsolidated deposits are thickest; also, water is confined in the deepest aquifers under a hydrostatic head as great as 1,500 feet. To the northeast the impervious beds feather out until a water-table condition is reached close to the foothills. In the same direction, the magnitude of the surge in wells decreased during the Long Beach earthquake. These features suggest that the amount of surge may have been controlled to a considerable degree by the thickness, perviousness, and elasticity of the water-bearing zones; also by the effectiveness of confining beds. However, if there were no other control, the proportionate water-level surge in a particular well should tend to be the same for all earthquakes except possibly those with epicenters within the immediate area. Such is not the case, as has been shown by the dissimilar effects of the Long Beach and Alaskan earthquakes on the one hand and the El Centro earthquake on the other. Some additional control must be effective. On Figure 4 the pattern of the lines of equal water-level surge suggests that the Newport-Inglewood fault-zone is such an additional control. It is postulated that this fault-zone locally resolved the forces set up in the bed-rock by the Long Beach earthquake and determined to a very considerable degree the direction and magnitude in which those forces were imparted to the overlying unconsolidated deposits. Obviously, the bed-rock forces set up by other earthquakes with various epicentral distances and directions might be resolved in diverse ways by this same fault-zone and by other features of geologic structure in the region. Thus, the proportionate water-level surges induced in a particular well might range decidedly.

An action of forces such as just suggested might explain the irregular relation that seems to exist between magnitude of water-level surge, epicentral distance, and earthquake intensity. For example, as Table 3 shows, during the El Centro earthquake a water-level surge occurred in a much greater proportion of wells in the Miami District, Florida, than in the Los Angeles Basin although the respective epicentral distances were roughly 2,000 miles and 175 miles. The wells in the Miami District find water in limestone which is little deformed. Earthquake waves would be transmitted more uniformly through this rock than through the diverse and complexly faulted consolidated rocks and discontinuous bodies of unconsolidated rocks that intervene between El Centro and the Los Angeles Basin.

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Table 3--Frequency of water-level surges in wells in the United States and Hawaii during the El Centro earthquake

[Largely after Thompson; data for the Los Angeles Basin by the writer]

Area	Number of wells with water-level recorders	Number of recorders showing water-level surge
Cincinnati, Ohio	15	0
Honolulu, Territory of Hawaii	--	3
Long Island, New York	20	0
Los Angeles Basin, California	25	13
Louisiana	--	2
Miami, Florida	14	10
Mississippi	--	3
New Jersey	45	0
New Mexico	--	4
Savannah, Georgia	--	2
Texas	--	4
Utah	30	7
Arizona, Arkansas, Connecticut, Iowa, Massachusetts, Oklahoma, and Tennessee	One or more	0

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EARTHQUAKE-RECORDS OF EPICENTRAL DISTANCE OF ABOUT TWENTY DEGREES

Daniel Linehan

(Abstract)

The discussion of this subject was in the form of a progress-report on the study being made of those quakes occurring just north of the West Indies and at a distance of about 20° to 30° from the New England group of seismic stations. Previous papers by the author on earthquakes in this area have been delivered before meetings of the American Geophysical Union.

Since the quake of June, 1939, no severe shocks have been felt whose origin was of that under discussion, and the number of minor ones recorded is not as great as in former years. The difficulty of accurate location of epicenter continues due to the lack of a sufficient number of suitably distributed stations with short-period instruments in the eastern section of the United States. The definition of phase-character is likewise so weak on the grams from the New England stations that epicentral distance is not too exactly determined in the case of most of the minor shocks.

The present paper also discussed the overhauling of the instruments at the station located at St. George's College, Kingston, Jamaica, British West Indies, by the author during the winter of 1940. An explanation of the site and equipment was given and credit given to those persons and foundations who made this important station possible. The intention of the Superiors at St. George's College to move this site outside the city where geological conditions would favor the study of these quakes was commended, as local geological effects hinder any greater magnification and short-period operation. At present, this is the only station in operation in the near vicinity and south of the seismic region under study.

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THE POSSIBILITY OF SEISMIC MEASUREMENT OF THE ROTATION OF THE EARTH'S CORE

Archie Blake

(1) Introduction--The calculations of Inglis show that the rate of transfer of angular momentum to the Earth's (liquid) core may be small enough to permit the axis of rotation of the core to lag about 2° behind that of the rock-mantle in the precessional motion of the Earth. The travel-time of P' would be altered by about one-fifth of a second, which is too small to be detected by a single observation made with even the best instrument, but can be brought out statistically when we have accumulated about three thousand clear measurements, on sensitive vertical-component seismographs, of the P'-waves from accurately located earthquakes.

(2) Effects to be expected--Elsasser [see 1 of "References" at end of paper] postulated convection in the core to account for the Earth's magnetism. The calculations of Inglis and Teller [2] indicate that the effect should be too small for the purpose. Inglis [3] finds, however, that the core as a whole may lag behind the mantle of the Earth as the latter undergoes its precession of period about 26,000 years. He estimates the angle of lag α at about 2°, but the approximations used are sufficiently uncertain that this angle may be wrong by a factor of 10 or so. Could this deviation be detected seismically?

There would be no Doppler effect, as there is no motion of the seismograph relative to the source, but only motion of the medium.

The redistribution of energy with epicentral distance would be too small to detect; the variation is ordinarily quite small even for considerable changes in distance. This does not apply in the immediate neighborhood of the focal point, though observations in this narrow range would be scarce. (See also the remarks at the end of Section 4.)

The effect on the travel-time of P', however, offers fair hope for detecting the rotation. There would be two effects: First, the bending of the seismic rays on entering and leaving the core would be altered by the rotation; second (the larger effect), the waves after penetrating the core would be carried along with it: both effects would change the travel-time. We proceed to the calculation of the magnitude of the change.

(3) Formulas--Denoting by α the angle between the axes of rotation of the Earth's core and mantle, and supposing with Inglis that their angular speeds are the same, ω, we have for the angular speed ω_r of the relative rotation vector the expression

$$\omega_r = 2\omega \sin (\alpha/2) \tag{1}$$

For small α, the ω_r-vector will lie approximately in the equator of the mantle; its direction, being fixed in space, will revolve relative to the mantle with a period of one sidereal day. The maximal relative peripheral velocity, lying approximately along the meridians of the mantle, will be of magnitude

$$v_r = \rho\omega_r \tag{2}$$

ρ being the radius of the core.

The bending of the ray on entering and leaving the core may be obtained by Huygens' construction. This determines the wave-fronts, hence the travel-times; but not the energy-distribution. (The energy-flux need not be perpendicular to the wave-fronts, cf. [4].)

In Figure 1 a ray is shown passing across a plane boundary in a medium in which the lower part moves relative to the upper with velocity v, the velocity of the wave having the same value, V, above and below the partition. The wave-front moves along the boundary with velocity V/s_1 relative to the upper stratum and therefore $[(V/s_1) - v]$ relativa to the lower; this relative velocity must be equated to V/s_2, provided this does not require $s_2 > 1$, and we have

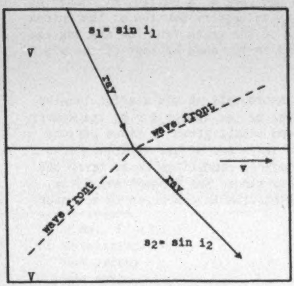

Fig. 1--Transmission of wave-motion into moving medium

$$s_2 = \frac{s_1}{1 - (vs_1/V)} \qquad \left(\left| \frac{1}{s_1} - \frac{v}{V} \right| \geq 1 \right) \tag{3}$$

If the condition indicated is not satisfied, such energy as is transmitted into the lower medium will not travel in plane waves. (It is of interest that (3) commutes with Snell's law but not, except for infinitesimal v, with itself.)

In the present application v is small compared to V, and the formula may be used for almost all values of s_1. In fact v is small enough here to make it desirable to use (3) in the limiting form

$$ds = s^2 \, dv/V \qquad (s \neq 1) \tag{4}$$

A seismic wave traveling with velocity V_m at the bottom of the mantle and V_c at the top of the core (considered as stationary) will be refracted according to Snell's law

$$s_c = (V_c \, s_m)/V_m \tag{5}$$

s_m and s_c being respectively the sines of the angles of incidence and refraction. The s_c provided by (5) is the s to be used in (4) in computing the change due to the rotation of the core.

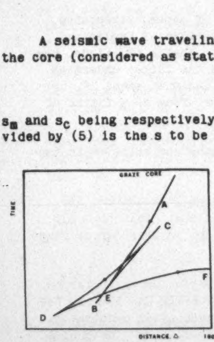

Fig. 2--P' travel-time curve (after Jeffreys, 1939)

For a ray whose parameter s_m in the mantle is fixed, the differential of the angle θ_c which it subtends at the center of the core, relative to the core, due to the rotation will be

$$d\,\theta_c = \frac{\partial \theta_c}{\partial s_c} ds_c \tag{6}$$

and the differential of the travel-time t_c in the core is

$$dt_c = \frac{\partial t_c}{\partial s_c} ds_c \tag{7}$$

the partial derivatives occurring in (6) and (7) being normally negative.

The increase in the epicentral angle Δ spanned by the ray will be obtained by adding to (6) the angle through which the core turns while the wave is passing through it

$$d\Delta = d\Delta_c = d\,\theta_c + t_c \, d\,\omega_r \tag{8}$$

To proceed from (7) to the differential of the time for the whole ray, we adopt the notations $(dt)_{s_m}$ and $(dt)_\Delta$ to denote the differentials respectively for fixed parameter s_m and for fixed Δ; they are related by

$$(dt)_\Delta = (dt)_{s_m} - \frac{\partial t}{\partial \Delta} d\Delta \tag{9}$$

and we have

$$(dt)_{s_m} = dt_c = \frac{\partial t_c}{\partial s_c}\, ds_c \tag{10}$$

To gather these results together we substitute (4) in the form

$$ds_c = \frac{s_c{}^2\rho \;\, d\omega_r}{57.296\ V_c} \tag{11}$$

(d $_r$ in degrees/sec) in (6) and (10); substitute (6) in (8); and substitute (8) and (10) in (9). We obtain

$$d\Delta = [\frac{\partial\theta_c}{\partial s_c}\,\frac{s_c{}^2\rho}{57.296\ V_c} + t_c]\ d\omega_r \tag{12}$$

and

$$(dt)_\Delta = [\frac{\partial t_c}{\partial s_c}\,\frac{s_c{}^2\rho}{57.296\ V_c} - \frac{\partial t}{\partial\Delta}\,\frac{\partial\theta_c}{\partial s_c}\,\frac{s_c{}^2\rho}{57.296\ V_c} - \frac{\partial t}{\partial\Delta}\,t_c]\ d\,\omega_r \tag{13}$$

We may simplify (13) slightly by substituting in the first term

$$\frac{\partial t_c}{\partial s_c} = \frac{\partial t_c}{\partial\theta_c}\,\frac{\partial\theta_c}{\partial s_c}; \tag{14}$$

we obtain

$$(dt)_\Delta = [(\frac{\partial t_c}{\partial\theta_c} - \frac{\partial t}{\partial\Delta})\,\frac{\partial\theta_c}{\partial s_c}\,\frac{s_c{}^2\rho}{57.296\ V_c} - \frac{\partial t}{\partial\Delta}\,t_c]\ d\omega_r \tag{15}$$

(4) Numerical results--Replacing the differentials $(dt)_\Delta$ and d $_r$ in (15) by the finite differences $(\delta t)_\Delta$ and $\delta\omega_r$, we have by (1), using Inglis' value $\alpha = 2°$

$$\delta\omega_r = 2 \times \frac{15}{60 \times 60} \times 0.01745 = 0.000\ 145 \text{ degree per second}$$

For the sake of internal consistency it is desirable to use data from one source in evaluating the coefficients for the core occurring in (15). The recent values of Gutenberg and Richter [5] are convenient, and are adopted for the present calculation. Our knowledge of the core is not yet very accurate, and the results we obtain will be subject to a little error, though much less than the uncertainty due to α.

We have ρ = 3446 km and V_c = 7.4 km/sec, V_m = 13.7 km/sec. The other quantities entering in the right member of (15) depend on the particular ray for which the formula is to be evaluated. We wish to consider the rays for which the hope of obtaining a measurable effect is most propitious. The general shape attributed [6] to the travel-time curve of P' is that shown in Figure 2. What parts of this curve are best for the present purpose?

To obtain the accurate measurements of arrival-times which we shall require, it is almost necessary that the motion to be measured be the first arrival on the seismogram. Phases arriving on an already disturbed trace are much more difficult to measure. This precludes all branches of the curve except BE and DF, and part of the latter, as the earlier P-wave continues perceptible in strong earthquakes to about 130°.

The sum of the first two terms in (15) is ordinarily almost zero; on examining the last term we see that the regions of steep slope of the travel-time curve are the most sensitive. The branch DF is almost useless from 160° on, where its slope approaches zero. We are confined, then, to the branch DF from about 120° to 160° and the segment BE, the latter extending from 142°5 to 149°3, approximately. (There may be a possibility that the whole segment BC could be used, the increased uncertainty in reading phases on a disturbed seismogram being offset in part by the steepness of the slope.)

We shall therefore evaluate (15) for two rays; the ray to the focus B, which is of special interest, and which will sufficiently represent the segment BE; and the ray for Δ = 140° on the branch DF, which will represent the segment of DF from about 120° to about 160°. The values of our parameter s_c for these two rays are respectively 0.391 and 0.227; the sin i_P in Table 22 of [5] is the s_m of (5). The values of θ_c in the respective cases are 101°5 and 119°1. $(\partial\theta_c/\partial s_c)$ is -126° for the focal ray and -770° for the other. We have also t_c = 584 sec and 639 sec in the respective cases, $\partial t_c/\partial\theta_c$ = 3.4 sec/deg and 1.8 sec/deg, and $\partial t/\partial\Delta$ = 3.1 sec/deg and 1.8 sec/deg.

These values substituted in (15) yield $(\delta t)_\Delta$ = - 0.27 sec and - 0.17 sec for the alteration in travel-time of the respective rays.

It is well beyond the power of the best available instruments to detect a deviation of one-fifth second in the arrival-time of P' in a single measurement. The determination is subject to the following uncertainties: (1) Identification of the beginning of P' on the seismogram; (2) timing error of the seismograph; (3) location of the epicenter of the earthquake; (4) time of origin of the earthquake; (5) depth of the earthquake-focus; (6) regional variations in travel-time (this effect would not be systematic on account of the revolution of the relative rotation vector with respect to the mantle).

Starting with items (4) and (5) in this list, we note that their effect is eliminated in comparisons between stations in opposite azimuths from an earthquake epicenter. How many such comparisons are available?

In answering this question we must consider the very important item (1), the identification of the beginning of P'. An earthquake wave after traveling all the way through the Earth is very attenuated, and can be clearly read on the records of very few types of seismograph. The longitudinal P'-motion is almost wholly vertical in direction and requires a vertical-component instrument of high sensitivity and preferably short period. The Benioff vertical seismograph meets these requirements, and the vertical galvanometric Galitzin and the vertical Quervain-Picard instruments approximate them. To show what data are available for the present purpose we list in Table 1 all stations equipped with these types of instrument, with dates of beginning of operation of the sensitive vertical seismographs.

It is seen that for a long time almost the only instruments of the kind required were located in Europe and Russia, but that a number of them have been installed in recent years in North America and a few elsewhere. For the bilateral comparisons desired we need stations located in or near the same meridian; the United States and Russia satisfy this condition, but would require earthquakes near the South Pole, which is not a seismic region.

Thus until the quality and distribution of seismograph stations are considerably improved we cannot hope for data by which to eliminate the uncertainties due to the time of origin and depth of the earthquake. Retaining, then, these two sources of error in our list, we estimate, for strong earthquakes observed with the sensitive instruments we have listed, that the standard error of a single comparison between the observed and scheduled arrival times of P' will be about 3 seconds.

The deviation of the travel-time, 0.2 sec, which we have computed would be reduced to about 0.1 sec by the consideration that most of the P'-waves that traverse the core would not receive the full effect derived on the supposition that the direction of the ray agreed with that of the relative motion of the core. To detect this effect it would be necessary to have enough observations to reduce the standard error to about 0.05 sec. (The comparison of phase with the independent magnetic result would be available.) The reduction from 3 sec to 0.05 sec, that is, by a factor of 60, would require about 3,600 observations. This is not beyond what we may hope to accumulate in a few decades. It seems very desirable that the installation of the best seismographs should become considerably more wide-spread (cf. [7], section 2).

The greatest uncertainty to which the foregoing computations are subject is that in α, the angle of lag of the axis of rotation of the core. The time-deviation and the number of observations required to detect it vary approximately as the first and inverse second powers of this angle, respectively. If the core should prove to be very inhomogeneous, lamination might considerably reduce the effect of turbulence in the transfer of angular momentum to the core, thus increasing the angle of lag. There is also a possibility that the wave PKKP, which traverses the core twice, could be used instead of P' to double the effect, but this wave is much harder to measure on seismograms.

In the foregoing calculation for the ray to the focus B in Figure 2 we used the right derivative $(\partial t/\partial\Delta)$ in evaluating (15). The left derivative of the first arrival-time is infinite: there is a small range of epicentral distance in which the rotation of the core will cause the first arrival to jump from B to the point above it on the branch DF or vice versa. The offset amounts to nine or ten seconds, which is easily observable. But there are two difficulties in this method. On evaluating (12) for the focal ray we find $\delta\Delta = 0\overset{\circ}{.}062$. First, observations within this narrow range of epicentral distance would be very scarce. Second, diffraction and regional variations might suffice to spread out the focus at B over a considerable width.

Table 1--Sensitive vertical-component seismographs of the world to 1940

(The Author would be grateful for any additions or corrections to this list)

Station	Instrument	Approximate date of installation	Remarks
Baku	Galitzin	January, 1925	
Basel	Quervain-Picard	January, 1934	
Berkeley	Galitzin	September, 1930	
	Benioff	October, 1933	
Buffalo	Galitzin	July, 1930	
Chiufeng	Galitzin	May, 1932	Suspended operation about June, 1937
Christchurch	Galitzin	September, 1931	
Chur	Quervain-Picard	< 1930	
Cincinnati	Galitzin	Summer, 1932	
Copenhagen	Galitzin	March, 1928	
	Benioff	December, 1936	
De Bilt	Galitzin	October, 1922	
Florissant	Galitzin	October, 1928	
Fordham	Galitzin	Late 1928	
	Benioff	September, 1937	
Georgetown	Galitzin	January, 1926	
Haiwee	Benioff	August, 1932	
Huancayo	Benioff	August, 1932	Some loss of record; not operating December, 1938, to February, 1940
Irkutsk	Galitzin	< 1924	
Ksara	Galitzin	1935	
Kucino	Galitzin	April, 1925	Discontinued December, 1934
La Jolla	Benioff	June, 1933	
La Paz	Galitzin	February, 1930	
Leipzig	Benioff	1938	
Leningrad	Galitzin	October, 1925	Discontinued June, 1927
Makeevka	Galitzin	October, 1925	Discontinued September, 1928
Manila	Galitzin	March, 1930	
Moscow	Galitzin	April, 1935	
Mt. Wilson	Benioff	January, 1933	
Neuchâtel	Quervain-Picard	< 1930	
Oak Ridge	Benioff	September, 1933	
Ottawa	Benioff	June, 1937	
Paris	Galitzin	≤ 1921	
Pasadena	Benioff	< 1931	
Pittsburgh	Benioff	April, 1935	Not operating 1937 to September, 1939
Pulkovo	Galitzin	June, 1923	
Riverside	Benioff	February, 1933	
Riverview	Galitzin	August, 1920	
Santa Barbara	Benioff	April, 1933	
Scoresby Sund	Galitzin	August, 1928	Not operating August, 1932, to December, 1933
Strasbourg	Galitzin	≤ 1919	
Stuttgart	Galitzin	February, 1930	
Sverdlovsk	Galitzin	≤ 1923	
Taschkent	Galitzin	≤ 1923	
Tiflis	Galitzin	January, 1928	
Tinemaha	Benioff	September, 1932	
Tucson	Benioff	July, 1936	
Uccle	Galitzin	< 1930	
Vladivostock	Galitzin	March, 1933	
Wellington	Galitzin	October, 1930	
Weston	Benioff	July, 1936	
Williamstown	Benioff	February, 1937	
Zikawei	Galitzin	February, 1916	
Zürich	Quervain-Picard	≤ 1924	

The second of these difficulties would tend to obviate the first. The transition from the branch DF to B might take place over an interval of 2° or so, thus providing a pseudo-slope $\partial t/\partial\Delta = -4.5$ sec/deg. The improvement over the former value +3.1 sec/deg is not very great, and the number of observations required to detect the rotation would not be reduced very far, especially as the standard error of an observation of the arrival-time might be somewhat larger than normal in this neighborhood.

The energy varies rapidly with epicentral distance in the neighborhood of the focus B. It is conceivable that this variation might provide as much or more information than the travel-time, but a quantitative treatment of this point will have to await more information on the energy near B. It will also be necessary to obtain the law of variation of the energy-distribution due to the rotation of the core, and in particular the accuracy with which (12) serves to approximate it.

I wish to express my thanks to J. D. Maddrill for his kindness in reading this paper in manuscript.

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U. S. Coast and Geodetic Survey,
Washington, D. C.

THE PROPAGATION OF AN SH-PULSE IN A LAYERED MEDIUM

C. L. Pekeris

(Abstract)

An exact solution is given for the problem of the propagation of an SH-wave due to a sudden application of a concentrated torsional stress at the surface of a layered medium. The solution is obtained in terms of elliptic integrals. The form of the displacement in the direct wave is like the time-derivative of the applied stress. The beginning of the refracted waves is like that of the stress. At moderate distances from the source the internally reflected waves are large and increase in relative magnitude with the abruptness of the stress. Figure 1 shows the

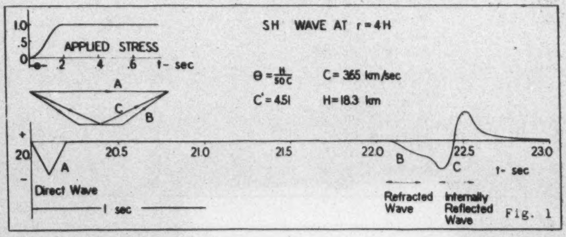

Fig. 1

displacement at r = 4H due to the application of a stress-pulse of the indicated form. It is suggested that the arrival-time of a totally reflected SH-wave should be taken at the point of maximum amplitude of the phase rather than at its beginning.

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PROGRESS-REPORT ON SEISMOLOGICAL ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY, APRIL 1, 1940, TO MARCH 31, 1941

Ralph R. Bodle

Teleseismic work--The following is a list of the seismological stations whose instrumental data are included in reports issued by the Bureau. Stations operated by the United States Coast and Geodetic Survey are: San Juan; Sitka; Tucson; and Ukiah. Stations operated on a cooperative basis with the United States Coast and Geodetic Survey are: Bermuda; Bozeman; Butte; Chicago; College; Columbia; Honolulu; and Salt Lake City. Stations operated independently are: Balboa; Burlington; East Machias; Huancayo; Lincoln; Logan; Montezuma; Philadelphia; and Seattle.

Also at the end of the period three seismograph-stations were in operation in the vicinity of Lake Mead. Temporary instruments were in use there pending receipt of new Benioff equipment. Plans are now under way to place seismographs in the immediate vicinity of Shasta and Grand Coulee dams. These projects are being sponsored by the Bureau of Reclamation and the United States Coast and Geodetic Survey with active cooperation from the National Park Service. Based on data accumulated to date, some progress was made in associating earthquakes and faults in the region of Lake Mead.

The Bureau cooperated with Spring Hill College (near Mobile, Alabama) by loaning instrumental equipment to aid in the test of a station-site. Cooperation of a similar nature was extended to the stations at Franklin Institute in Philadelphia and at the University of Vermont at Burlington, Vermont.

Further improvements have been made in the methods of driving recording drums. The principal advancement is the adaptation of a small dry-cell driven motor eliminating the use of storage-batteries.

The Work Projects Administration Office in Philadelphia continued the interpretation of seismograms from cooperative stations throughout the year and made considerable progress in bringing the publication of teleseismic results up to date. Publication is now about a year behind schedule.

Records were loaned to cooperating organizations including St. Louis University, California Institute of Technology, and the University of Pittsburgh.

Immediate epicenter-determination--Through the cooperation of the Jesuit Seismological Association, Science Service, and the United States Coast and Geodetic Survey, immediate epicenter-results were obtained for publication by Science Service. The Survey issued epicenter-cards for 35 earthquakes during the 1940 portion of the year, and five to the end of March, 1941.

Strong-motion work--Annual reports of the strong-motion work done by the Bureau on the Pacific Coast and in the Western Mountain Region are published in the Bulletin of the Seismological Society of America. During the period of this report there were 13 earthquakes and a number of aftershocks which produced 43 accelerograms and six displacement meter records. The earthquake of March 18, 1940, in the Imperial Valley was the principal earthquake of the year. This shock was destructive and was recorded by strong-motion instruments at considerable distance from the epicenter. Analysis of the El Centro accelerogram of this shock has revealed a great deal of valuable information for the engineer as well as information of great interest to the geologist and the seismologist. The final report on this work is now in preparation.

Both accelerograph and displacement-meter records were obtained for the Eureka shock of December 20, 1940. A preliminary analysis of the accelerogram and comparison with the displacement-meter record show definite evidence that displacements computed from the accelerograph-record can be relied upon within the range of periods affecting engineering requirements.

In addition to maintenance work, progress was made in the development of the multi-pendulum recorder. A shaking table was rebuilt in the San Francisco Office to give a period-range from 0.2 to 12 seconds. It was then used to test an experimental displacement-meter.

Tilt-meter observations were continued at Berkeley with the cooperation of the University of California. Seismic acoustic work was suspended throughout the year because of the lack of funds.

Non-instrumental work--Felt data are collected by mail and field-canvasses of felt areas for use in determining the limits of the affected areas and for the purpose of locating minor shocks for purposes of record. Many organizations and individuals cooperated in this work. In California active cooperation was continued by the University of California, the California Institute of Technology, several large commercial organizations, and a large number of individuals. In other Western States, State collaborators gave effective cooperation. The Jesuit Seismological Association and the Northeastern Seismological Association in the eastern part of the country continued the active cooperation of former years.

Miscellaneous--The annual publication "United States earthquakes, 1938" was issued during the year and the 1939 issue was in preparation at the end of the period covered by this report.

The quarterly report "Abstracts of earthquake reports for the Pacific Coast and Western Mountain Region" has been issued through March, 1940.

The quarterly "Progress report on strong-motion work" has been issued for the last quarter of 1940.

The mechanical enlarging apparatus was further improved and has been effective in the saving of considerable time as well as improving accuracy obtained in the integration of accelerograms.

A representative of the Bureau was appointed as a representative of the Soil Mechanics and Foundation Division on the Joint Committee on Seismology of the American Society of Civil Engineers.

U. S. Coast and Geodetic Survey,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30 - MAY 3, 1941

JOINT MEETING, EASTERN SECTION, SEISMOLOGICAL SOCIETY OF AMERICA AND SECTION OF SEISMOLOGY -

REPORTS AND PAPERS

WASHINGTON, D. C.
MAY 2, 1941

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REPORTS AND PAPERS, JOINT MEETING OF SECTION OF SEISMOLOGY AND EASTERN SECTION OF SEISMOLOGICAL SOCIETY OF AMERICA

GEORGETOWN UNIVERSITY

9:00 A.M., MAY 2, 1941

ROCK-BURST RESEARCH AT LAKE SHORE MINES, KIRKLAND LAKE, ONTARIO

ERNEST A. HODGSON

The conditions under which a miner works are hazardous at best. Most of the hazards (gas, rock-falls, explosions, etc.) can be anticipated so that steps may be taken to minimize, or even eliminate, them. Where mines are carried to depths of 2,000 feet and more, a hazard appears which, so far, has not been found to give invariably definite evidence of its magnitude or even of its presence. This is the rock-burst.

Whatever other pressures may be present at depth, one is certain--the pressure due to superincumbent rock. Until the mine-workings make excavations at depth, the rock at deep levels is held in place by pressure from all sides, which, at depths of half a mile or so, tend to become pseudo-hydrostatic in nature. When this pressure is relieved by mine-workings on one or more sides of a section of rock, its strength can no longer sustain the load. Pieces spall or fly from the face of workings, some so small that they do no serious damage even if they do happen to strike a man. Casualties are confined to an occasional cut from a sharp fragment. At other times, pieces weighing several pounds will be thrown off from the surface (floor, walls, or roof of an excavation) as one might pinch a melon-seed between thumb and finger. A burst of this type can cause serious injury and even death. Such failures, large or small, are called strain-bursts. In some cases the walls will snap in such a burst without any rock spalling from the surface.

If a volume of rock under pressure is exposed on two or more sides, it is referred to as a pillar. The progress of mining operations may tend to diminish the size of a pillar and/or to throw extra weight upon it, until finally the pressure per square inch becomes more than the rock can sustain. The whole pillar may burst, sometimes throwing down tons of rock and perhaps overloading adjacent pillars so that they too burst, practically simultaneously or perhaps after the lapse of an interval which may be minutes or even days. A failure of this type is designated a crush-burst.

The energy released in a crush-burst may approach that of a small earthquake. Eight of these, occurring at Lake Shore Mines, are known to have been the cause of records on the short-period Benioff at Ottawa ($\Delta = 280$ miles). Gutenberg and Richter state that the energy released in the smallest recorded earthquakes is of the order of 10^8 ergs. Computations show that sufficient energy could be stored in the rock, due to the burden of superincumbent rock alone, to account for that evidenced by these records. While other pressures may exist, it is not necessary to postulate them in order to explain the source of energy evidenced.

The factors which determine the time and place of a rock-burst are many. Most of them cannot be measured. Even the fact of the existence of some of them in any particular case is often uncertain. The depth of the workings, the shape and size of the openings and their distribution as a whole throughout the mine, the strength or brittleness of the rock, the geology of the region in general and of the workings in particular, the mining methods employed, the rate of mining--these are only a few of the many conditions which determine if, when, and how a pillar will burst. The discussion of these factors is beyond the scope of this brief paper but they must be studied in the mine itself by those responsible for applying geophysical means for their evaluation, if progress is to be made in this type of research.

Rock-bursts cannot be prevented. They can be controlled to some extent by proper choice of mining methods. These are designed to work hand in hand with the rock-bursts, so to speak. Heretofore, the mining industry has depended solely on the good common sense and painfully acquired experience of its best miners. This, thoughtfully applied, has helped very greatly to reduce the damage and casualties arising from rock-bursts. The mining industry now asks whether geophysical means can be found to supply data for the guidance of their men as they excavate to greater depths. The general principle followed is to so arrange the methods and speed of mining that the rock may be induced to burst under conditions which will not cause great reservoirs of strain to build up without release. The geophysicist is asked to devise for their guidance some means for determining where and to what extent the strains are developing.

The rock-burst study at Lake Shore Mines began when, in January, 1939, this Company asked the Dominion Observatory to arrange the installation of a surface-seismograph to record the occurrence of rock-bursts and their relative intensities. The installation was completed and began operation on December 19, 1939. The equipment consists of a Heiland geophone such as is used in seismic prospecting which registers by means of a galvanometer on a recording drum giving 30 mm/min line speed. The geophone and recording pier were placed on solid rock in a specially constructed basement room of a dormitory.

The recorder was designed and built by the Heiland Research Corporation, Denver, Colorado, and has since been somewhat modified in the light of experience. It now records all the larger blasts as small displacements from the record line in addition, of course, to the larger strain-bursts and all the crush-bursts. While the Heiland recorder was being modified from time to time, one of another type was used in its stead so that the operation of the seismograph has been practically continuous since December 19, 1939.

One of the main reasons, from the point of view of the Observatory, for devoting the time to installing and maintaining this seismograph has been for the purpose of timing the bursts so that the travel-time to distant seismographs could be determined. To this end, the installation includes a HRO radio receiver, a Dent chronometer, and all accessories for timing the minute-signals and obtaining the correction automatically by radio.

During 1939, while the equipment was being designed and built, seven crush-bursts occurred at Lake Shore Mines of sufficient intensity to register at Ottawa. Since the surface-seismograph was installed, no burst has occurred of that intensity. So, thus far, no measure of the travel-time has been obtained, although more than a hundred bursts of noteworthy intensity have registered at Kirkland Lake. However, the service is operating continuously; and, should a major burst occur, valuable travel-time data will be obtained.

In January, 1940, Lake Shore Mines invited the Dominion Observatory to organize rock-burst research in the mine. A mine-seismograph was designed and assembled at Ottawa using a Heiland geophone and a Brush crystal-detector as alternative pick-ups and an ink-recorder designed and assembled by V. E. Hollinsworth of the Observatory staff. On the recommendation of the Observatory, the mine engaged Zack E. Gibbs to assist for a month in tentative experiments at the mine. Mr. Gibbs has had wide experience in the application of electronics to seismic exploration. The tentative experiments were carried out in March, 1940.

It was found that underground conditions were such that recording bursts for a statistical study is out of the question without special precautions being taken. Blasts and other mine-noises kept the mine-seismograph in a constant state of unrest. However, on the basis of the experience gained, recommendations were made for a program of instrumental development which was to take at least a year. As a preliminary, a well-equipped electronics laboratory and workshop was considered a necessity.

Several possible lines of investigation were suggested in addition to the development of a mine-seismograph which would respond to bursts alone. These included: Measurements of variations of velocity of sound through pillars presumably undergoing increasing strain; development of strain-meters; metric studies of active faults; attempts to measure temperature-variations due to variations in pressure; and attempts to detect and register supersonic vibrations, if, as suspected, these occur in a pillar subjected to increasing strain or pressure.

The program was accepted. Mr. Gibbs was engaged for the work and the laboratory was built and equipped with the recommended instruments and tools. This was done with remarkably little delay considering the disruption to business due to war-conditions. At the time of writing, a full year of this work has been completed and arrangements have been made to continue it indefinitely.

Based on the experienced gained in the March experiments a new mine-seismograph was designed and built by Gibbs, using a commercial Esterline-Angus ink-recorder and the pick-ups already tried, together with other crystal-detectors sensitive to still higher frequencies. It was suspected that vibrations in the rock caused by blasting might have a frequency which differs from that caused by bursting. Several attempts to measure these frequencies failed, so a regular seismograph-prospecting outfit was leased from L. Don Leet of Harvard University. This was used in Lake Shore Mines and also in the Frood Mine at Sudbury which shared the expense of obtaining the equipment.

It was found that blasts induce a frequency of from 40 to 60 cycles per second, while that due to bursts ranges from a little over 200 to more than 400 cycles. Other mine-noises, hoists, tramming, ore-chutes, crushers, etc., induce frequencies less than 100 cycles. It then appears possible to devise a filter which will enable the mine-seismograph to register only bursts.

It was early recognized that if the frequencies differ it was to be expected, a priori, that burst-frequencies would accompany some of the blasts for these undoubtedly release strain in the rock. Experiment confirmed the deduction. Some blasts show high burst-frequencies, superposed on their own low frequencies. Some blasts do not. The records, where good fortune enabled the experimenters to catch a strain-burst when no blasting occurred, showed no low frequency.

It was difficult to obtain a suitable filter, owing to the pressure of war-work. Finally, computations were furnished by one company and the filter built by another. After some experimenting by Gibbs the characteristics of the equipment as measured in the laboratory were found to suppress the registration of frequencies under 200 and to give good amplification for those above. This equipment has had only a few days use in the mine and some experimenting will be necessary to find a location where the blasting will be far enough distant that it will not force its way through the network but that bursts can still record. It is believed that this is only a matter of time and experiment and that compilation of burst-data can soon be undertaken as routine.

A strain-gage of hydraulic type was designed and built and has been in continuous operation in a particularly bad part of the mine since August 26, 1940. Since then two heavy and other smaller bursts have occurred in the vicinity. It appears that there is a sort of hypothetical straight-line graph, the inclination of which shows the average rate of closing-in of the stope. For some weeks prior to each of the two large bursts, the graph fell below this line and, at the time of bursting, abruptly rose to meet it. Further experience is necessary but the results to date have been very encouraging.

An electric gage was designed by V. E. Hollinsworth of the Observatory staff for rapid checking of master-gages. The device is very sensitive, showing a deflection of about a quarter of an inch on the meter for a movement of 10^{-5} inch at the gage. It was believed that such a gage could yield valuable information if designed to be placed deep in a diamond-drill hole run into a pillar.

The gage, redesigned with this object in view, was tried out at the mine by Hollinsworth and Gibbs in late March, 1941. Experiments in the laboratory showed that a drill hole 1.5 inches in diameter in a piece of rock about the size of a football could be deformed sufficiently by pressure with the hand alone to show deflections by means of the microgage installed in the hole. No difficulty was experienced in installing the gage at any desired depth in drill holes in the mine. But, difficulties were found in obtaining sufficiently constant voltage for successful continued operation.

Pending the delivery of equipment ordered for further experiments in the mine, two sets of the gage and its accessories are being arranged for--one at the mine and one at Ottawa. At the mine, Gibbs will experiment with the view to obtaining the necessary constant power-supply and in ironing out other difficulties connected with continued registration. At Ottawa, Hollinsworth will use the gage to obtain the pressure-strain curve for large samples of rock, bored at the mine, and supplied for these experiments. The pressures, applied by a hydraulic press, will be carried up to the point of failure of the specimens.

As soon as the equipment is ready for further experiments underground, the work will be resumed at Lake Shore Mines. It is believed that this method promises interesting data of a very local character. It is evidently most desirable to be able to measure strictly local conditions. The details of the gage and the results of the experiments will be reported later.

Steps have been taken toward developing equipment for detecting and recording supersonic vibrations in pillars. Delays in obtaining parts are responsible for no progress in experiments having been made to date. This method is considered most promising. It should, if successful, yield data which will also be of a local character. No work has so far been attempted with thermometric devices; and, except for a few tentative shots with Leet's equipment, no measures of sound-velocity have been made. Regular seismic equipment would have to be greatly modified for such work and for the moment it is not planned to attempt this method.

Dominion Observatory,
Ottawa, Canada

THE ANALYSIS OF THE EL CENTRO RECORD OF THE IMPERIAL VALLEY EARTHQUAKE OF MAY 18, 1940

Frank Neumann

The following is a summary of the conclusions reached after an exhaustive analysis of the strong-motion accelerograph record obtained by the United States Coast and Geodetic Survey at El Centro, California, at the time of the destructive Imperial Valley earthquake of May 18, 1940. The details of this investigation will appear in a forthcoming report of the Coast and Geodetic Survey.

The El Centro record of May 18, 1940, is one of the most, if not the most, valuable strong-motion records obtained to date, and an investigation of a type not previously attempted is now nearing completion. After converting the active portion of the three acceleration-curves to velocity and displacement and constructing resultant-motion graphs for limited periods of time, the following conclusions can be drawn: (1) In the epicentral area the same laws of seismic-wave propagation are found as in the case of distant earthquakes, that is, the resultant ground-motion is apparently a combination of longitudinal and transverse waves which is not seriously disturbed by the slipping motion along a nearby fault; (2) dominant periods, for the shorter-period waves, are clearly in evidence only in directions which are longitudinal and transverse with respect to the direction to the epicenter; (3) along oblique coordinates, not "square" with the epicentral direction, the longitudinal and transverse waves in the shorter-period range combine in such a complex pattern that dominant periods are practically non-existent and the period-amplitude graphs are merely smooth curves or envelopes which embrace wide ranges of periods; (4) fairly reliable curves are now available to show, for the more complex type of record, the variations of acceleration, velocity and displacement with period; (5) from a study of rotational characteristics of the resultant-motion graphs, it is found that rotational motions are of definite periodic (reversing) character. The details of this study are being written up in a special strong-motion report and will be made available before the final report on the Massachusetts Institute of Technology shaking-table tests. These results may be highly significant in solving some of the fundamental problems of seismological-engineering research.

U. S. Coast and Geodetic Survey,
Washington, D. C.

AMATEUR SEISMOLOGY

Joseph Lynch, S.J.

(Abstract)

The two instruments that seem most feasible for worth-while amateur work in seismology are the Sprengnether-Macelwane electromagnetic seismograph, which Mr. Sprengnether is willing to construct for $160, and the Joliat optical seismograph, both vertical and horizontal. Details of both will be published later.

During the year, the following colleges were visited with a view to arousing Amateur Seismic interest: Carleton College; St. Catherine's College; St. Thomas' College; and St. Benedict's College--all in Minnesota--Milton College in Wisconsin, and Bowdoin College in Maine. All promised active cooperation in the future.

Fordham University,
New York, New York

EARTHQUAKES OF THE NORTHEASTERN SECTION OF THE UNITED STATES AND EASTERN CANADA DURING THE YEARS 1938, 1939, AND 1940

Daniel Linehan, S.J., and L. Don Leet

(Abstract)

Twelve seismic stations at present comprise the Northeastern Seismological Association and the present paper demonstrates the number and locations of local quakes recorded by these stations during the past three years. Ninety-five quakes are listed and numbered, and several of these have been treated in detail.

A comparison is made between the epicentral map of these three years with former maps,

showing distribution and number of quakes felt and determined.

(Note: The manuscript of this paper is being sent to the Bulletin of the Seismological Society of America for publication.)

Weston College (D.L.),
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Cambridge, Massachusetts

THE MOODUS EARTHQUAKES AND THE CAUSE OF EARTHQUAKES IN NEW ENGLAND

Elmyn L. Perry

The occurrence of two small earthquakes at Moodus, Connecticut, early in March, 1940, has presented a fresh opportunity to study this active seismic area and to review its history. The writer is indebted to the Connecticut Geological and Natural History Survey for permission to use parts of an unpublished manuscript, by the late Professor Wilbur Foye of Wesleyan University, dealing with the seismic history of the region as one phase of his study of the Eastern Highlands of Connecticut.

Moodus, in the township of East Haddam, has long been famous for its earthquakes and earth-noises. The latter are sounds undoubtedly associated with seismic activity but occurring at times when no perceptible shock is noted. No record has ever been kept of the numerous small shocks which have occurred here since colonial days, but there is every indication that the total must be several hundred. About a dozen larger shocks, probably ranging between V and VI on the Rossi-Forrel scale, have been noted and one shock has been estimated at VIII, that is, strong enough to crack the walls of buildings. The following notes on the early seismic history were assembled by Dr. Foye [see 1 of "References" at end of paper]:

"The most severe earthquake (in the region) occurred at Moodus in the north part of East Haddam on May 16, 1791. Reverend Henry Chapman found a diary of the occurrences of that date and transmitted it to Professor Benjamin Silliman who published it in his journal [2].

"It began at 8 o'clock p.m. with two very heavy shocks in quick succession. The first was the most powerful; the Earth appeared to undergo very violent convulsions. The stone walls were thrown down, chimneys were untopped, doors which were latched were thrown open, and a fissure in the ground of several rods in extent was afterwards discovered. Thirty lighter ones succeeded in a short time, and upwards of one hundred were counted in the course of the night.

"This shock was felt at a great distance. It was so severe at Killingworth (now Clinton) that a Captain Benedict, who was walking the deck of his vessel then lying in the harbor at that place, observed the fish to leap out of water in every direction as far as his eye could reach.

"The atmosphere was perfectly clear and pleasant and the moon which was near its full, shone remarkably bright. On the night of the 17th six more were observed. The atmosphere was still clear and warm."

In the letter transmitting this record, Reverend Chapman included other remarks about the town of Moodus. "East Haddam was called by natives 'Morehemoodus', or place of noises, and a numerous tribe of cannibals resided there. They were famous for worshipping the evil spirit, to appease his wrath. Their account of the occasion of the noises is 'that the Indian God was angry because the English God intruded upon him, and those were the expressions of his displeasure.'"

Much earlier another minister, the Reverend Jeremiah Hobart, had mentioned the Moodus noises. In a quaint memorial to the Connecticut General Assembly in May, 1702, "praying that measures should be taken to enforce his claim against the people of Haddam for arrears of salary he facetiously recites that he is 'not fond of our lost neighbors' (the people of East Haddam) and then expresses the hope that the 'strange bellowing noises and earthquakes lately heard may awaken them to righteousness'" [3].

A somewhat later mention of the noises is contained in a letter from Reverend Stephen Hosmer who lived at Creek Row, a short distance south from Mount Tom in Moodus. It was written to Reverend Thomas Prince of Boston and dated August 13, 1729 [4]. "As to the earthquakes I have something considerable and awful to tell you. Earthquakes have been here (and nowhere but in this precinct, as can be discerned: that is they seem to have their center, rise, and origin among us), as has been observed for more than 30 years. . . . Whether it be fire or air disturbed

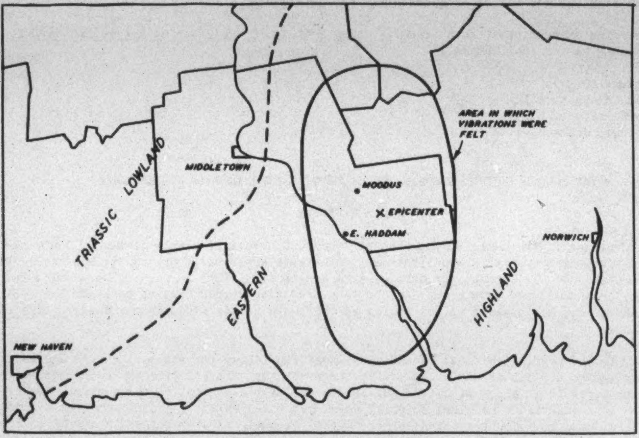

Fig. 1--Sketch-map of south-central Connecticut showing location of Moodus and area affected by 1940 earthquakes

in the subterranean caverns of the Earth cannot be known; for there is no eruption, no explosion perceptible, but by sounds and tremors, which sometimes are very fearful and dreadful, I have myself heard eight or ten sounds successively and imitating small arms, in the space of five minutes. I have, I suppose, heard several hundred of them within 20 years, some more, some less terrible. Sometimes we have heard them almost every day, and great numbers of them in the space of a year. Oftentimes I have observed them to be coming down from the north, imitating slow thunder, until the sound came near or right under, and then there seemed to be a breaking like the noise of a cannon shot, or severe thunder, which shakes the houses and all that is in them. They have in a manner ceased since the great earthquake (probably the Newburyport earthquake of November 8, 1727). As I remember there have been but two heard since that time, and those but moderate."

It is quite clear from the above that Moodus was the scene of considerable seismic activity during the eighteenth century and more complete records show a somewhat comparable history for the nineteenth century. The known dates and periods of activity in Moodus and nearby areas are listed in Table 1. The "Moodus noises" reported so fully by the early observers have been the subject of much speculation and many folk-lore tales [5]. They are, however, a phenomenon repeatedly observed in connection with earthquakes in many parts of the world and have been the subject of extensive review and discussion by Davidson [6]. Apparently Moodus is so situated in a valley between rocky hillsides that the short-period seismic vibrations are transmitted directly from bare rock into the air and are much more perceptible than in regions with a more extensive mantle of soil.

The two earthquakes of March 2 and 13, 1940, seem to be typical of Moodus earthquakes as described in the past and are also typical of earthquakes elsewhere in the New England region. The 1940 shocks were felt over an area measuring about 20 miles north and south by 12 miles east and west, as indicated in Figure 1, which is based on data collected by the United States Coast and Geodetic Survey from postmasters within 30 miles of the epicenter and from field-studies by the writer. Very little variation in intensity was noted in different parts of the disturbed area. In the villages of Moodus and East Haddam most observers remarked as to the strong vertical component of the motion and many householders thought that a minor explosion had occurred in their basement furnaces or coal-bins. Very few observers noticed any lateral motion even in the outer part of the disturbed area.

All of the evidence gathered in the field seems to indicate a focus well below the surface for both of the 1940 shocks, although no exact estimate of the depth can be made from the data

Table 1--Partial list of Connecticut earthquakes

Date	Origin
1700 to 1727 (several)	East Haddam
1791, May 16 (R-F VIII) many after shocks	East Haddam
Aug. 28	East Haddam
1792, Jan. 11	East Haddam
Oct. 24	East Haddam
1793, July 6	East Haddam
1794, Mar. 6	East Haddam
1805, Aug. 11	East Haddam
Dec. 30	East Haddam
1812, Feb. 9	East Haddam
July 5	East Haddam
1813, Dec. 28	East Haddam
1827, Aug. 23	New London
1837, Apr. 12	Hartford
1840, Aug. 9 (R-F VI)	"North of New Haven"
1844, June ?	East Haddam
1858, June 30 (R-F IV)	Near New Haven
1860, Mar. ?	East Haddam
1862, ---	Colchester
1875, July 28 (R-F VI)	Northwest Connecticut
1886, Sep. 5	East Haddam
1894, Apr. 10	East Haddam
1897, Sep. 5	East Haddam
1899, May 16	East Haddam
1908, Feb. 5	Housatonic Valley
1913, Nov. 15	East Haddam
1916, Dec. 2	East Haddam
1917, Feb. 16	East Haddam
Mar. 11 (4 shocks)	East Haddam
1919, Aug. 11	East Haddam
1925, Nov. 14	Near Hartford
1927, Aug. 20	East Haddam
1937, July 27	Rockville
1938, June 13	Bethel
June 14	Bethel
Aug. 2	Southwest Connecticut
Sep. 20	East Haddam (?)
1939, Aug. 12	East Haddam (?)
1940, Mar. 2	East Haddam
Mar. 13	East Haddam

at hand. It is the opinion of the writer that a depth of at least ten miles would be required to satisfy the conditions implied by observations made during the quakes as to the character of the motion and extent of the disturbed area.

Professor Foye has commented on the lack of evidence of surface faulting as follows [1]: "No major fractures have ever been discovered in the rocks about Moodus. The region is underlaid by the Hebron mica schist, a metamorphic rock derived from sandy mudstone. During the mountain building of mid-Paleozoic age these schists were intruded by pegmatitic granites which seam the hills with white layers. Cave Hill, from which some say the vibrations emanate, is capped by a flat sheet of pegmatitic granite. . . . . J. B. Woodworth and the writer (Foye) searched the area for glaciated surfaces, hoping to discover a displacement of the smooth planes. None were found here, but elsewhere in New England displacements of one or two inches are known [7]. They indicate that since the glacial period, only slight displacement of the Earth's crust have occurred in this area. Nor are any pre-glacial faults known in the rocks of this vicinity. If any fractures are present they are so minute that they are not easily detected. Immense faults are known along the contact between the red sandstones of the Connecticut Valley and the crystalline rocks of the Eastern Highlands but no movements occur on these faults at the present time since towns located along this line are relatively least liable to earthquake disturbances." (The fault mentioned is about nine miles west of Moodus.)

Instrumental data gathered by the Benioff stations at Fordham, Harvard, Weston, and Williamstown [8] indicate that the epicenter of the quakes of March 2, 1940 (H = 04-15-36.0), and March 13, 1940 (H = 01-29-00.0), is located at longitude 72° 25!7 west and latitude 41° 28!2 north. The first-mentioned stations are about equidistant from the epicenter, while Williamstown is some 15 km farther away, but the four stations are so placed as to give good triangulation. Since the observing stations are so nearly equidistant they afford a check on only a small part of Leet's New England travel-time curves [9]. The Williamstown grams for both earthquakes are essentially identical down to the most minute details and both apparently check remarkably well with Leet's curves, although under the circumstances the persistence of particular phases cannot be checked over a significant distance and the exact identification of phases only a second or so apart is open to criticism under such conditions. Records of all three components (Benioff) for the earthquake of March 2 were kindly loaned by Weston College and are compared with the Williamstown record in Table 2.

One of the most striking features of the several records is the presence of a strong "false S" phase [9] preceding the probable S_2 and it is unfortunate that the data at hand do not permit a fuller study of this interesting phase. In view of the probable depth of focus of the Moodus earthquakes it was considered possible that the phase in question is actually S_2 arriving early but this same early phase has been noted on seismograms of blasts where there can be no doubt that the depth of focus is negligible.

All of the evidence at hand points to a deep-crustal or sub-crustal (?) locus for the

Table 2--Phases registered at Weston and Williamstown from the Moodus earthquake of March 2, 1940, as interpreted from the Harvard travel-time curves

Phase	Weston (139 km)	Williams (152.5 km)
	h m s	h m s
P_2	04 15 58.9	04 16 00.8
P_1	04 15 59.5	04 16 01.2
P_1P_1	04 15 59.9	04 16 01.7
$2(P_1P_1)$	04 16 01.1	04 16 02.2
P_1S_1	04 16 02.8	04 16 04.8
F	04 16 13.9	04 16 17.5
S_2	04 16 15.6 ?	04 16 19.0
S_1	04 16 16.5	04 16 20.2
S_1S_1	.. ..	04 16 21.0

persistent stresses giving rise to these earthquakes, although the exact cause can not be demonstrated from field-evidence. The usual, and often the only, cause assigned to earthquake-stresses in the New England region is that of isostatic adjustment following the melting of the last ice-sheet in the Pleistocene. This idea was first advanced by Hobbs [10 and 11] to explain certain Michigan earthquakes and has recently been elaborated by Daly [12]. According to the latter earthquakes are to be expected along the general zone of the Whittlesey and Algonquin hinge-lines. Moodus is located about half way between these two hinge-lines (extrapolated) and is also on the zero-isobase line as calculated from post-Pleistocene coastal elevation. In other words, Moodus is in an almost ideal location to fit the glacial control-theory.

On the other hand, an inspection of any good maps of epicenters in the eastern United States, such as Heck's [13] or Woollard's [14] shows that Moodus is located within a well-defined seismic belt extending along the older Appalachians from Alabama to the Maritime Provinces. There is obviously no possibility of genetic connection between glaciation and the occurrence of earthquakes in most of this belt and they are most probably related to isostatic adjustments connected with the Appalachians. There is ample evidence of such adjustments during the Cenozoic, as shown by the warped and uplifted peneplanes throughout the region and the demonstrated movements far exceed any adjustments related to glaciation. It is considered highly probable that movements similar to those known to have occurred in the past are still proceeding, although quite possibly at a slower rate.

There is apparently some coincidence of the Appalachian seismic belt with lines of gravity-anomalies, as recently summarized by Swick [15], but here again exact correlation is not possible from present data. The evidence indicates that Moodus is situated midway between an area of positive anomalies in western Connecticut and an area of negative anomalies in the Narragansett Basin.

In contrast with the well-marked Appalachian belt of geologic structures and seismic activity trending northeast-southwest, there is no obvious belt of epicenters trending westward from New England as would be expected under the glacial control-theory. The writer therefore feels that, while the glacio-isostatic theory must undoubtedly be considered as a possible cause of earthquakes in the northeastern States, the bulk of the evidence points to other causes (of isostatic adjustment). Certainly the coincidence of numerous earthquakes with uplifted areas not only in the Appalachians, but also the Adirondack Dome, the Ozark Dome, and possibly the Cincinnati Arch, is too striking to be overlooked, although a complete case for genetic connection may not be possible at present. The writer therefore believes that the long-continued seismic activity at Moodus and other Connecticut localities is an indication that this region is still playing an active role in the geologic history of the Appalachians.

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Williams College,
Williamstown, Massachusetts

INSTRUMENTAL STUDY OF THE NEW HAMPSHIRE EARTHQUAKES OF DECEMBER, 1940

L. Don Leet and D. Linehan, S.J.

(Abstract)

A study of original records and bulletin readings for two strong earthquakes in the Ossipee Mountain District of southeastern New Hampshire in December, 1940, gave for both $\varphi = 43° 50'$ north, $\lambda = 71° 17'$ west.

S started from a depth of approximately 35 km and P at the same time from a depth of 15 km. The second shock was multiple. Times at the focus were: 1940 December $20^d\ 07^h\ 27^m\ 26^s$; $24^d\ 13^h\ 43^m\ 45^s$; $24^d\ 13^h\ 43^m\ 47^s$; $24^d\ 13^h\ 43^m\ 57^s$.

The velocities observed, in km/sec, were

P_{1+2}	6.44	S_{1+2}	3.82
P_3	7.30	S_3	4.02
P_n	8.44	S_n	4.43

Mechanism at the focus probably differed from that of earthquakes which involve surface-faulting, with elastic potential playing a negligible role for the first quake and a possible but indeterminate role in the second. First motion from the second quake was reversed from that of the first at nearby stations. There were no foreshocks preceding the first quake, a small one just before the second, and only ten aftershocks with the last one on February 12, 1941 (up to the date of writing, April 28, 1941).

The Richter magnitude was at least 6 for the first and slightly greater for the second main shock. From this, the energy can be computed as 10^{20} ergs or 7.4×10^{12} foot-pounds. This ranks both shocks as potentially destructive. They were felt to a distance of 350 miles, which means an area of potential perceptibility of 385,000 square miles.

Harvard Seismograph Station (L.D.L.),
Cambridge, Massachusetts
Weston Seismograph Station (D.L.),
Weston, Massachusetts

MACROSEISMIC STUDY OF THE NEW HAMPSHIRE EARTHQUAKES OF DECEMBER, 1940

James J. Devlin, S.J., L. C. Langguth, S.J., and R. L. Arringdale

(Abstract)

Residents of New Hampshire in the vicinity of Tamworth felt two principal shocks during December, 1940, one on December 20 and the second on December 24. Questionnaire cards were used to canvass the area as well as the radio, press, and several days by the authors in the region were well spent in visiting residents and noting the damage effected.

At least 600 separate items were used to study these quakes, and it was deemed necessary to make the study of both quakes at the same time first since the epicenter seemed to be one for both, and again the people would compile data for both on the same card and it was difficult to differentiate between one quake and the other. Many claimed that the second shock was of greater intensity than the first.

The damage consisted mostly in fallen chimneys, although near the center some houses were entirely shifted on their foundations, one to a great degree. The intensity at the center was rated at VII on the Rossi-Forel scale.

(Note: Manuscript sent for publication to Bulletin of Seismological Association.)

Weston Seismograph Station (J.J.D. and L.C.L.),
Weston, Massachusetts
Portland Seismograph Station (R.L.A.),
Portland, Maine

THE NORTH CAROLINA EARTHQUAKE OF DECEMBER 25, 1940

V. C. Stechschulte, S.J.

(Abstract)

A small earthquake occurred in northwestern North Carolina about 1:47 a.m., eastern standard time, December 25, 1940. Shocks were recorded at approximately this time at Cincinnati, St. Louis, Pittsburgh, Williamstown, Weston, and Fordham, but attempts to correlate the readings suggest that the New England stations recorded a different shock occurring at nearly the same time. A number of small shocks have occurred in this general region of the Appalachians in recent years.

Xavier University,
Cincinnati, Ohio

TRAVEL-TIME TABLES FOR NEAR EARTHQUAKES IN EAST-CENTRAL NORTH AMERICA

Edward J. Walter and Henry F. Birkenhauer, S.J.

(Abstract)

These tables are based on studies made at St. Louis University by Edward J. Walter of six near earthquakes occurring to the south of St. Louis and by Henry F. Birkenhauer, S.J. of eight near earthquakes occurring to the east and northeast of St. Louis. In both investigations an endeavor was made to find the crustal picture and velocity-values which would best account for the observed arrivals of earthquake-waves.

For the region to the south of St. Louis the crustal structure was found to consist of an upper layer five km thick underlain by a layer 20 km thick which rests upon a layer 12 km thick above the normal substratum. The velocities of compressional and shear waves for these layers are as follows:

Layer	Thickness	Phase-velocity	Phase-velocity
I	5 km	P_1 6.03 km/sec	S_1 3.63 km/sec
II	20 km	P_2 6.33 km/sec	S_2 3.74 km/sec
III	12 km	P_3 7.19 km/sec	S_3 4.08 km/sec
Normal substratum		P_4 7.73 km/sec	S_4 4.40 km/sec

For the region to the east and northeast of St. Louis the crustal structure was found to be more complex, consisting of an upper layer five km thick underlain by three layers of thicknesses 8, 12, and 12 km in order of increasing depth above the normal substratum. The compressional and shear wave velocities for these layers are:

Layer	Thickness	Phase-velocity	Phase-velocity
I	5 km	P_0 5.62 km/sec	S_0 3.52 km/sec
II	8 km	P_1 6.03 km/sec	S_1 3.63 km/sec
III	12 km	P_2 6.33 km/sec	S_2 3.74 km/sec
IV	12 km	P_3 7.19 km/sec	S_3 4.08 km/sec
Normal substratum		P_4 7.73 km/sec	S_4 4.40 km/sec

Times of arrival for the five P-phases and the five S-phases of the latter crustal structure as well as the five (S - P)-intervals were calculated. These times have been compiled into a table which is serviceable for identifying phases in either crustal picture with the exception that the slowest phases P_0 and S_0 are not to be expected in earthquakes from southern azimuths.

St. Louis University,
St. Louis, Missouri

SURFACE-WAVES IN HETEROGENEOUS MEDIA

James T. Wilson

(Abstract)

Solutions have been obtained and dispersion-curves calculated for surface-waves of the Love and Rayleigh types in media in which the elastic constants are exponential functions of the depth. Both sets of waves show dispersion of the expected type and for oceanic paths the agreement between observed and calculated values is satisfactory.

University of Michigan,
Ann Arbor, Michigan

TRIALS OF GALVANOMETERS OF VARIOUS PERIODS WITH ELECTROMAGNETIC SEISMOMETERS

William A. Lynch

(Abstract)

Galvanometers with a variety of periods have been tried with electromagnetic seismometers in order to extend the usefulness of the latter. It has been known for a long time that a filtering effect is obtained by the use of seismometer and galvanometer so that certain earth-vibrations are suppressed and others are magnified. The Benioff seismometer as usually employed is equipped with a short-period galvanometer with a period about a fifth of a second and a long-period galvanometer with a period of about a minute. Recording has been improved greatly by the use of three galvanometers, namely, the original short-period, a Leeds and Northrup Type-R with a period of 4.5 seconds, and a Leeds and Northrup Type-P ballistic with a period of 25 seconds.

It has been found possible to increase the effectiveness of the Galitzin-Wilip instruments in the same way. The horizontal seismometer has been used with its regular 14-second galvanometer and the 1/5-second at the same time; local earthquakes and blasts are recorded by the short-period while teleseisms are recorded on the longer-period galvanometer as usual. The 4.5-second galvanometer responds particularly well to the reflected phases of teleseisms when connected to the Galitzin vertical, at the same time that the 14-second galvanometer records all phases with unimpaired clearness. A Type-P student galvanometer has given excellent records on the Galitzin horizontal while connected in parallel with the regular 14-second galvanometer; it records both primary and secondary waves with exceptional clarity; its period is 6.5 seconds.

Microseismic disturbances on the 4.5- and 6.5-second galvanometers have been much less than anticipated; often the regular 14-second galvanometers of the Galitzins have been affected much more than these when connected to the same instruments.

Experiments are continuing with more galvanometers of different characteristics so that the whole range of periods may be investigated experimentally.

Fordham University,
New York, New York

PROGRESS-REPORT ON PERIODICITY AND TIME SERIES

Archie Blake

(Abstract)

Classical methods for detecting and measuring periodicity have suffered from two serious defects. First, the Schuster periodogram does not provide adequately for non-sinusoidal types of variation. Second, the smoothness encountered in almost all time series and many other types of data introduces a spurious appearance of periodicity which vitiates the test of significance unless proper allowance is made for the smoothness.

New statistics designed to detect effects not contemplated in the Schuster periodogram are being tried in a study of the series of aftershocks of the Helena, Montana, earthquakes of October, 1935. This work is being done by use of punched cards, which greatly alleviate the labor of the computation.

In the case of two types of departure from randomness, such as periodicity and smoothness, each effect disturbs the statistics designed to detect the other. The only rigorous treatment is to study them together, but approximate methods (for example, that of Bartels) for discounting the effect of one type of variation in studying the statistics designed to detect the other may be very useful.

Thus the accurate detection of periodicity demands a treatment of the problem of detecting, describing, and measuring the smoothness exhibited by the series under test. This problem has been discussed by Bartels, Jeffreys, and others, and from a different point of view by Shewhart The methods of the last named have been made the subject of considerable extension within the last year or two.

U. S. Coast and Geodetic Survey,
Washington, D. C.

REPORT OF COMMITTEE ON METHODS AND OPERATIONS, EASTERN SECTION, SEISMOLOGICAL SOCIETY OF AMERICA, 1940

Elmyn L. Perry, Chairman

Introduction

The Committee on Methods and Operations was first authorized and organized in 1938 (Cambridge-Weston meeting) to gather information on the actual operating practices at the eastern seismograph stations and to make available such information to the members of the Society. The Committee was thus to serve in large part as a clearing-house for the exchange of ideas on operating methods, new devices and instruments. The Committee personnel for 1938-39 and 1939-40 consisted of E. L. Perry, Chairman, E. A. Hodgson, M. K. Hubbert, J. B. Macelwane, S.J., and F. Neumann.

No formal questionnaire was circulated but an outline of suggested topics was sent to eastern stations by the Chairman with a request for comment. Only a few stations were canvassed in 1938-39 but a considerable amount of material for a trial report was obtained, edited and issued in mimeographed form at the 1939 (New York) meeting. The present report for 1939-40 is based on the earlier report with additional material gained by canvassing all eastern stations and from discussions at the 1940 (Cincinnati) meeting. It has been found that there is some overlap with the work of the committees on Vault Construction and on Amateur Seismology although this has been avoided as far as possible.

The work of this Committee could obviously be continued as long as progress continues at the eastern stations and it remains to work out a simple procedure for making annual increments to this present basic report. It is suggested that the outline accompanying this report will, if modified from time to time, serve as a convenient base for the collection and classification of material for publication in Earthquake Notes each year, following an annual request for information from all eastern stations. The Committee and the officers of the Eastern Section would appreciate suggestions and criticism on this and other phases of the Committee's work.

In the report which follows Your Committee has given no extensive descriptions but has rather attempted to indicate the nature of various ideas, devices, and methods and to show where fuller information may be obtained.

Classification of information

- (I) Operation of seismometers and recorders
  - (A) Shielding devices (temperature, air-currents, etc.)
  - (B) Calibration, test-forces, etc.
  - (C) Optical systems
  - (D) Damping
  - (E) Motors
  - (F) Construction of instruments and parts
- (II) Electrical circuits
  - (A) Control-boards, switches, etc.
  - (B) Transformers
  - (C) Rectifiers
  - (D) Conduits, shielding, etc.

- (III) Timing
    - (A) Radio control
    - (B) Methods of recording time-signals
    - (C) Master-clocks
- (IV) Records
    - (A) Type of paper
    - (B) Developers and fixers
    - (C) Technique of developing
    - (D) Washing and drying
    - (E) Trays and tanks
    - (F) Reading of records, lenses, scales, etc.
    - (G) Enlarging and copying
    - (H) Filing of records
- (V) Public relations
    - (A) Handling of visitors
    - (B) News items
    - (C) Programs of public education

(I) Operation of seismometers and recorders

(A) Shielding devices (temperature, air currents, etc.)--U. S. Coast and Geodetic Survey has developed metal covers for seismometers; these are sealed to base in oil or vaseline to guard against moisture and air currents. Drying tubes with $CaCl_2$ are provided. Shields for large tilt-compensated instruments have also been worked out. Photographs and data are available.

Butte and Logan are reported to use water-filled tanks surrounding the instruments and vermiculite has also been used as an insulating material.

Ottawa reports that the Wiechert vertical at Victoria is enclosed in a wooden case fitted with a simple thermostat developed at the Dominion Observatory. Particulars concerning this thermostat which is both sensitive and rugged, operating from the standard lighting circuit, may be obtained from Ottawa.

Pittsburgh reports the use of glass in aluminum frames to shield the individual instruments and also the entire vault-top. Photographs are available.

Weston suggests using heavy cord packed in felt, such as used on large refrigerators, to pad doors to cut down air currents.

See report of the Committee on Vault Construction (Section 15) for a discussion of control of humidity; St. Louis, Fordham, and Georgetown may be able to offer practical suggestions to those with problems in this field.

U. S. Coast and Geodetic Survey has used clear glass, such as used in the windows of motion picture projection-booths, to carry light-beams through metal instrument-housing.

Williams has found ordinary red cellophane useful for reducing stray light, for example, covering a viewing window in the recording room and covering a small flashlight used around the recorders.

Summary--A wide variety of shielding and insulating materials is evidently in use at different stations, but those mentioned above serve to illustrate the chief types.

(B) Calibration, test-forces, etc.--Ottawa has replaced the ordinary Benioff device for adding the test-weight, with an electrically operated mechanism. The weight is suspended by a silk thread from the lengthened armature of an ordinary relay; closing the circuit adds the weight. The silk thread runs through a guide-hole in a metal cap which fits over the hole in the standard Benioff frame. The relay is mounted on a wooden frame independent of the seismometer. A key in the seismometer-room and another in parallel in the recorder-room provide convenient means of applying the weight as required.

St. Louis reports calibration of the Wood-Andersons by a mirror on the side tilt-screw and the telescope and long scale furnished with the Galitzin-Wilips. A similar method of calibration is used for the Macelwane seismographs.

U. S. Coast and Geodetic Survey dynamic tester for Wenner: Special electrical circuit arranged to apply a definite electromotive force to seismometer alone, deflecting it a certain amount. After a steady state is reached the special circuit is broken and the galvanometer connected, resulting in a definite deflection of the galvanometer. Photographs are available.

(C) Optical systems--U. S. Coast and Geodetic Survey reports the use of "first surface aluminized" mirrors, 3 by 5 inches, mounted on heavy stands, to change direction of light-beams, in satisfactory manner.

Ottawa has replaced all Wood-Anderson and Milne-Shaw mirrors with "first surface aluminized" mirrors furnished by the respective manufacturers. The results indicate marked improvement.

Dr. Rude (Massachusetts Institute of Technology) suggests that the new coated, "no-glare" glass may be of value in eliminating "ghosts" from optical systems so troubled.

It is also suggested that "polaroid" may have some possible value in optical systems.

(D) Damping mechanisms--U. S. Coast and Geodetic Survey reports use of new cobalt steel and Alnico magnets permitting magnetic damping even on large seismometers of Bosch-Omori type. Efficient damping on small instruments is now possible with a single magnet! Photographs are available.

St. Louis reports that the new Macelwane seismographs are damped with Alnico magnets and copper vanes.

(E) Motors--U. S. Coast and Geodetic Survey reports development of a direct-current motor-governor for use on small direct-current motors in localities where the frequency-control on alternating current is not reliable. This was discussed by Mr. Nelson at the Cincinnati meeting.

Weston and Williams have had some trouble with motors (furnished with Benioffs) slowing down or speeding up in spite of uniform current-frequency. No scientific reasons have been assigned.

All stations bothered by alternating-current frequency variations are urged to get in touch with their power-company and ask for cooperation.

(F) Construction of new or improved parts, etc.--U. S. Coast and Geodetic Survey reports a new lightweight multiplying lever for the Milne-Shaw, made of one piece aluminum wire and equipped with plano-convex mirror. Photographs are available.

U. S. Coast and Geodetic Survey advises new non-magnetic coils and parts for the Wenner seismometers to give more uniform performance over the full amplitude.

Harvard, Ottawa, and Pittsburgh report the construction of drums locally; Ottawa can furnish data on theirs which were made in Dominion shops. Harvard has used lead shot in the drum as a load to keep the drum at uniform speed. Ottawa reports using a drum with a small flap cut in the surface; this flap lifts to insert the paper which is then passed through and clamped on the inside in taut position.

Pennsylvania State advises using half-inch elastic bands to hold the paper on the drum; Xavier (Cincinnati) uses a steel "bicycle-clip." U. S. Coast and Geodetic Survey reports the use of lucite strips for holding grams--lucite is less fragile than the usual glass strips.

No general comment on shops which can do custom work can be made at this time since experience to date is often irrelevant in the face of national-defense work.

The report of the Committee on Amateur Seismology should be consulted for information on inexpensive machines and parts.

(II) Electrical circuits

(A) Electrical control-boards, switches, etc.--Harvard, Weston, Pittsburgh, and Williams as well as a few other stations carry all electric circuits through a central control-panel outside the vault. The first three stations mentioned use essentially standard radio racks and panels while the Williams installation is a small "home-made" one mounted on Masonite. Photographs may be available from U. S. Coast and Geodetic Survey and from Pittsburgh. The central panels are chiefly useful where the station master-clock and radio time-control can be mounted nearby.

(B) Transformers--Williams has found a second-hand, six-volt radio transformer to be very useful for lamp-circuits because of its large current-capacity as compared with "toy-transformers." Weston uses the same type of transformers as Williams, but with two in parallel because of a heavier load on the line (six lamps) and so that if one transformer goes wrong the other can carry the load temporarily.

Several stations use "toy-transformers" for lamp-circuits; for example, Pittsburgh has used an old 150-watt type with excellent results and South Carolina reports using a Jefferson adjustable type with adjustable rheostats in the lamp-circuits to permit control of the current to each lamp and prevent overload if one lamp burns out.

(C) Rectifiers, etc.--Weston, U. S. Coast and Geodetic Survey, and others have had considerable success in using low-voltage direct-current directly from standard commercial copper-oxide rectifiers. Pennsylvania State, for example, uses a B-L Electric Manufacturing Co. (St. Louis) Type-B, 120L, 6-volt and St. Louis also uses B-L rectifiers exclusively.

Harvard considers the Gibbs special rectifier (see Earthquake Notes, September, 1938) to be very reliable and to have proved itself at that station.

Williams has been using six-volt direct-current directly from an old Westinghouse "trickle-charger" for operation of the time-marking circuit; no battery is used. Pittsburgh reports using two Marquette trickle-chargers to maintain voltage on two storage-batteries which actuate all relays.

South Carolina has found it advisable to float two Edison four-volt batteries across the G-M copper oxide rectifier to give a steady current for magnets which are used to shift the light-spot; this system is at a disadvantage when the main current goes off as the battery sends a current back through the rectifier.

At the special Canadian station at Kirkland Lake a motor-generator, running constantly, floats the storage-battery for the 3.5-ampere lamp of the special Heiland seismograph.

(D) Conduits, shielding, etc.--See Section 16, report of Committee on Vault Construction, 1940.

The main problems center around the use of pipe-conduits, conduit-wound cables, or "open" wires and these in turn seem to depend on the humidity of the vault. It is the general, although not unanimous, opinion that pipe-conduits are almost sure to cause trouble sooner or later and that wiring should be high, dry, and accessible.

(III) Timing

(A) Radio control--General: Radio reception varies so much at different seismograph stations that few generalizations can be made and each station must work out its own solution to the problem. Father Linehan suggests that "before spending too much money on present-type radios it might be well to see what modulated-frequency transmission might do in the case of time-signals."

Several stations use the National SW-3 (short-wave) radio for signals from Ottawa and from Arlington.

Harvard, Weston, and others use a long-wave receiver for the Arlington 113-kc signals, which are said to be less subject to fading.

St. Louis uses National SW receivers (for Arlington 9425-kc) except in St. Louis itself where an "HRO" is used to obtain greater selectivity; these are all used for automatic recording.

Pittsburgh reports remodeling two different types of standard radio receivers for automatic reception of signals; the cost is said to be about $10.00 for remodeling.

(B) Methods of recording time-signals--General: Three methods seem to be in general use for recording the clock-correction from radio time-signals: (1) "Log-book" notation of correction from direct comparison of clock-signal and radio signal; (2) manual recording of signals on the record as they are received; and (3) automatic recording of radio signals on the record.

Williams, using the first and second methods, has found it very useful to plot a graph of the clock-corrections in order to assist in interpolation on the records and also to keep a better check on the behavior of the master-clock.

Most of the U. S. Coast and Geodetic Survey and cooperating stations are now recording signals on the grams manually from the radio signals.

St. Louis uses automatic recording by adding another amplification-stage beyond the loud speaker and a low-resistance telegraph-relay; radio and relay are in the laboratory with wires extending to the vault.

Pittsburgh uses the plate-circuit of the second detector to run a Dunco Model CXB-51 sensitive relay which in turn controls the regular drum-relays.

Automatic recorders for radio time-signals are used regularly in Canada at Victoria, Kirkland Lake, Shawinigan Falls, and Seven Falls. The Dominion Observatory signals are relayed through the CBC network at 1 p.m. eastern standard time, permitting these signals to be recorded even when static conditions are bad.

(C) Clocks--No information has been received on the types of master-clocks in use or on problems relating to their regulation and maintenance.

(IV) Records

(A) Types of record-paper or film--Several types of paper are in use at the various eastern stations, among them: "Eastman News Bromide," "Eastman P.M.C. No. 2 Bromide," "Insurance Bromide, Grade A," and "Haloid Record, Grade B."

Prices range from about $18.00 a gross up to about $28.00 a gross, depending upon the weight of paper, type of surface, etc.

Descriptive lists of record-papers may be obtained directly from the Haloid and Eastman Kodak companies. Agfa does not seem to carry record-paper in regular stock. The Gaevert Company is at present establishing a manufacturing plant in Williamstown, Massachusetts, and as soon as it goes into production a report will be made on any record-papers available.

Weston advises that if film is used, as on the newer Benioffs, acetate and not nitrocellulose should be used because of the long life of the former.

General: This Committee is planning a more extensive study of different varieties of paper in the near future.

(B) Developers and fixers--Eastman D-72 and Agfa N-103 developers are in general use and seem to be voted the most convenient to use although many other prepared developers are satisfactory, for example, Haloid M-Q which is recommended for Haloid papers.

Prepared acid "hypo" fixing powders (Eastman, Agfa, and Haloid) seem to be in general use.

Eastman Kodak can furnish a booklet on "Stains on negatives and prints," a problem of possible interest to some.

(C) Technique of developing--Each station has developed its own technique in this field to suit local conditions. Tray-development of single sheets, or two sheets back to back, seems to be common practice. Some stations develop the paper spread out in a tray large enough to take the record paper extended, while others use a small tray and loop the paper through the solution constantly during developing.

The Haloid Company can furnish a description of "Processing photo recording papers" by Jno. J. Johnson; this refers specifically to records obtained in geophysical prospecting but is also of general interest.

(D) Washing and drying--Both broad shallow tanks, for washing the paper in horizontal position, and deep tanks for the paper suspended on end are in use. One of the best washing systems is in use at Weston where several records are fastened to a rack in extended position and the whole unit lowered vertically into a wash-tank (stoneware).

Drying may be done on frames covered with cheese-cloth, using an electric hair-dryer or an electric fan where speed is essential. The most pretentious arrangement is a "Pako" rotary photo-dryer in use at Weston (three minutes per record). Eastman suggests using a "Photo blotter roll," 11-1/2 inches by 6 feet, at about $1.50. This consists of a cloth-covered blotter, a regular blotter, and a corrugated cardboard in which the records may be rolled; this is described on page 13 of the "Velox booklet."

Father Linehan of Weston offers the following comment: "Trouble is often observed in preserving paper against cracking or curling. 'News Bromide' or 'Kodalith' are preferable to other papers for the clarity of detail in the record but the former will crack very easily and the latter curls. Haloid papers and Insurance Bromide will wrinkle, and are in general not as good as the other two for clarity of detail and prevention of halation. Eastman Kodak has a new product on the market called 'Flexol', which seems to be a glycerine compound, and the records are washed in this before drying but after washing. Not much is known of the efficacy of the process as it has not yet been sufficiently tested."

(E) Tanks and trays--Each station has met the problem of construction of tanks and trays to suit local conditions and many interesting variations have been worked out.

Harvard uses a special bench with four built-in lead-lined sink sections: (1) 16 by 16 by 3 deep for developer; (2) 12 by 24 by 9 deep for general service; (3) 24 by 40 by 9 deep for washing; and (4) 15 by 38 by 3 deep for fixing. An additional acid-stop-bath tray might also have been added.

Weston uses vertical stoneware-tanks for hypo and washing, with a galvanized-iron tray, painted with "Kodacoat" for developer.

Williams tried a hypo tank of galvanized iron and "Kodacoat" but it proved to be very poor and now uses either a well-waxed wooden box or a large glass jar in which the paper can be partially coiled and stood on its side. A satisfactory wash-tank was made of galvanized iron and Kodacoat, 40 inches tall and about 14 by 5 in section, with a feed-pipe running to the bottom and fitted with hose-connections for input and overflow; papers are suspended from wooden clothes-pins and weighted with Eastman film-clips.

U. S. Coast and Geodetic Survey has used well-waxed wooden trays slightly larger than the records. Eastman Kodak can furnish instructions for making similar inexpensive sinks and trays.

Pittsburgh had two monel metal trays made in their shop; size 12 by 4 by 36 inches, total cost about $35.00. Outlet tubes in the ends make for ease in handling solutions.

South Carolina has been using a lead tray supported by a wooden box for washing, a battery-jar for hypo, and glass trays for developer.

St. Louis has had sheet-iron trays prepared and then had them enameled at moderate cost in St. Louis; their fixing tank is a 20-gallon earthenware jar.

Inexpensive trays for developing and fixing may be made by coating parafine wax over the two parts of the box in which the sensitive paper is shipped.

A very complete discussion of the relative value of various materials used for tanks and trays is found in an Eastman Kodak pamphlet, "Materials for the construction of photographic processing apparatus" by Crabtree, Matthews, and Muehler of the Kodak Research Laboratories.

(F) Reading of records, lenses, scales, etc.--Several stations use low-power binocular microscopes and cylindrical reading lenses as an aid in interpretation. U. S. Coast and Geodetic Survey notes the use of 3/4-inch glass rod for a cylindrical reading lens.

Weston uses special scales marked in seconds, according to the scale of the record. Metal or white ("composition") scales (Keuffel and Esser) marked in 1/2 mm seems to be more or less standard.

U. S. Coast and Geodetic Survey uses some photographically reduced scales (from drawings) photo-printed on aluminum. A practical scale may be made with a sharp, hard pencil on a 3 by 5 card, where a rather closed scale is used on the gram.

Ottawa suggests the use of a slide-rule for reading in interpolated positions on seismograms of different minute lengths; this is convenient and well within the limits of accuracy involved.

No special problems are indicated in this field, although a study of the limits of accuracy of the reading scale in terms of the accuracy of timing is perhaps in order.

(G) Enlarging and copying records--Harvard, Weston, Williams, and perhaps others, use opaque projection-equipment to enlarge records for study and copying.

Weston reports the use of "Kodalith" paper for contact-prints in copying. This technique probably deserves more attention with a listing of papers available and equipment necessary.

Williams has used a glass-topped copying frame, lighted from below, for copying records onto adding-machine paper; this is of particular value in "untangling" the interlocking records of large distant quakes.

Records may be copied by photostat, contact-print or blue-print. U. S. Coast and Geodetic Survey says: "There is probably only one satisfactory way of enlarging records--that is, the enlarging camera."

(H) Filing records--Marking records: Most stations have their own satisfactory system of stamping each record with the date and other relevant data. Weston has devised a system of marking the component and direction of earth-movement photographically on each record before developing; this is done by exposing the end of the record to a lantern-slide (negative) mounted in a light-box near the proper drum. Particulars may be obtained from Weston.

Filing records: This is largely a local problem at each station. At Harvard and Weston, for example, filing is done in drawers and according to date. The latter station advises alternating the records, one day face up the next face down, etc., to take care of curling. Some stations file each month's records strapped between thin boards. Ottawa separates records into quake and non-quake and then files in large envelopes marked with a standard form to show the contents; the quake-records are filed by quake-number for each year (following the Dominion Observatory reports) and the "dead" records are filed by date. U. S. Coast and Geodetic Survey also advises the use of manila envelopes for each month's records. Some stations file in the boxes in which the sensitive paper is shipped; this is satisfactory if the boxes are overfilled and stacked so as to exert pressure on all the sheets.

Micro film: It is suggested that many stations will have to turn, ultimately, to micro film in order to conserve storage-space. Such a practice might lead to the establishment of reference collections of great value to the science and may be worth investigation in the near future.

(V) Public relations

(A) Handling of visitors--Weston, with a large number of visitors, advises making explanations outside the vault, using photographs, etc., so as to cut down the time that visitors are in the recording vault. At Weston and Williams the seismometers are separate from the recorders and are viewed only through a window; much the same situation obtains at Harvard as far as viewing is concerned. Pittsburgh also follows the same general plan of explaining outside the vault and admitting only special visitors to the vault. Pennsylvania State advises using a visitors book to be signed with the time of visit to assist in identifying associated disturbances on the records.

Ottawa is experimenting with the design of an ink-recorder to duplicate the regular record of a Benioff seismograph. This would be used in the entrance hall of the Observatory and would make it possible to handle the increased number of visitors who attend the open Saturday nights after a large earthquake.

On the whole it would seem advisable to have at hand a prepared display (outside the vault) for lay visitors; always assuming that the good will of visitors is a valuable asset to the science and worth some thought and attention.

Note: The broad subject of "public relations" has been considered by the Committee only from the standpoint of the "handling of visitors," other items for future consideration are suggested below.

(B) News items--(1) Systematic issue of bulletins on large or local earthquakes; (2) informal or formal interviews; (3) "feature articles."

(C) Public education--(1) Periodic observance of "open house"; (2) lectures; (3) museum displays (permanent or temporary).

Supplemental report by the Committee on Methods and Operations of the Eastern Section, Seismological Society of America

The Committee on Methods and Operations of the Eastern Section, Seismological Society of America, for 1940-41 is constituted as follows: E. A. Hodgson; M. K. Hubbert; J. H. Nelson; V. C. Stechschulte, S.J.; E. L. Perry, Chairman.

During 1940-41 the Committee has gathered information with which to supplement the report of 1939-40 under the following headings: (III-C) Master-clocks; (IV-A) types of recording paper; (V-B,C) news items and public education.

Copies of the report of 1939-40 were sent to most of the operating stations in the United States of America and Canada and opportunity was given to contribute to this year's report on the topics listed above. Questionnaires were filled out and returned by some 15 stations or groups of stations. The results of the inquiry are summarized below.

Master-clocks--(1) The commonest clocks used are standard Seth Thomas with the following also mentioned: Spindler and Hoyer; Wiechert; Shortt; E. Howard; Springfield; Thiel; and Cincinnati Recorder.

(2) Nine stations reported the clocks to be in the vault and six in rooms near the vault. Ten reported no attempt at temperature-control while two mentioned local insulation and three have thermostatic control. There is no apparent relation between the rigidity of temperature-control and the ability of the station to keep the daily correction low.

(3) The range of rate-control varies greatly from 0.1 sec/day to 6.0 sec/day although most stations keep the rate well under 2.0 sec/day. St. Louis points out that almost any change per day is permissible provided that it is regular and known. Most stations keep the rate so low that the uncertainty in any one minute is far below the limits of readability of the record to say nothing of the errors introduced by paper-shrinkage, etc. The greatest care would seem to be needed in understanding the actual behavior of the clock within any given day to assure that the rate of change is a linear function.

General: comments, questions, and problems--Burlington (University of Vermont) reports that barograph-records plotted against clock-gains and losses seem to indicate that varying atmospheric pressure is a factor in rate-change (mercury pendulum-clock).

Pennsylvania State asks for information on photo-electric instead of direct contacts and the effect on clock rates.

Pittsburgh asks for discussion of the feasibility of using crystal-controlled clocks in seismograph-stations.

East Machias (Massachusetts Institute of Technology) would like information on the best clock-oil for a clock subjected to a wide range of temperatures.

Recording papers--The following papers are reported to be in use at the present time in various stations returning questionnaires:

(1) Eastman News Bromide (single, glossy, contrast) rated very satisfactory by two stations; cost high.
(2) Eastman Recording No. 2 used by one station; good contrast but sometimes brittle.
(3) Eastman Insurance Bromide, Grade A used by U. S. Coast and Geodetic Survey stations and some others; ratings vary from very satisfactory to unsatisfactory. Several stations mention wrinkling and shrinkage particularly. Apparently local conditions affect the usefulness of this paper considerably.
(4) Canadian Kodak PMC No. 2 Bromide used by Canadian stations; satisfactory.
(5) Haloid Record B used by five or six stations; cost low, tends to fog unless considerable care is exercised, otherwise satisfactory.
(6) Haloid Record A used by one station; no comment.

Apparently there is no one paper which is ideal in the light of the several factors which must be weighed in selecting a paper for any one station. The following factors have been mentioned:

(1) Cost: This varies from about $18 to $30 per gross for paper of the size used on the Benioffs. Xavier reports some saving by purchase in rolls rather than sheets.
(2) Contrast and fogging: This depends in large degree on the light-intensity and the paper-speed in use as well as stray light in the work rooms, that is, on local conditions.

(3) Readability, that is, sharpness of definition: It is implied by some stations that this is related to the character of the surface of the paper (glossy) although it is actually related to the grain-size in the emulsion used, according to the manufacturers. Apparently some stations are using paper which the manufacturers intended for quite different work.

(4) Wrinkling and uneven shrinkage: No generalizations possible.

(5) Cracking: Glossy papers are reported to give trouble (for example, Harvard).

(6) Response to humidity: The variation in paper-size with varying humidity in the vault is apparently a serious problem for some stations. In this connection Ottawa reports that "in order that the recording paper shall conform to the recording drum throughout the exposure-period, provision nas to be made for paper-expansion due to moisture-absorption. This is met by placing a day's supply of photographic paper in a light-tight humidifier-box in the recorder-room for a 24-hour period in advance of its use for recording." East Machias (Massachusetts Institute of Technology) asks "what paper shows the smallest dimension change with humidity." Williams has found that a well-dried record shows a shrinkage-equivalent to 0.5 sec/min but that this can be offset by returning the record to the vault for rehumidification before reading.

General: comment, questions, and problems--Pittsburgh suggests a "movement to ask photographic supply people to put on the market a paper which will give high contrast, bind easily, and not wrinkle. Cost of $25 per gross is not too much." In this connection your Chairman has already approached the Gaevert Company, which is now constructing a manufacturing plant in Williamstown, Massachusetts, and has been assured that as soon as they are "in production" their chemist will be glad to study our particular problems and make up trial-lots of paper.

Pennsylvania State asks for "information on drying procedure and drying devices, to obtain fairly rapid drying but avoid wrinkling and non-uniform shrinkage of paper." Harvard is also interested in this same problem.

Harvard reports that "glossy records (subject to cracking) which we want to handle for classroom use or exhibition we mount with Chartex Cloth ($18.50 per 100-foot roll 36 inches wide). This is applied by ironing without special professional experience necessary."

College-Alaska reports the satisfactory use of Insurance Bromide A for contact-prints from original records if the prints are made while the record is still wet so that good contact is made.

Public relations--Few worth-while generalities can be formulated from the questionnaires sent out on "public relations" since each station has its own local problems.

All stations report some contact with the press but statements indicate that the exact method of cooperation varies. Several stations work through a university Press Bureau or Public-Relations Office as much as possible, some work directly with reporters or editors personally known to them, while several wait for the papers to take the initiative. Harvard, particularly, expresses the opinion that "the subject gets better handling if releases are confined to ones which the press itself decides have news value." Many stations mention the value of working with the press since the press in turn often furnishes immediate data on important quakes and so assists with location of epicenters.

Three stations in particular stress the fact that extreme care should be taken in formulating statements for the press, especially as concerns predictions and guesses from too little fact since these often open the science to ridicule. "Feature-stories" are mentioned as particularly dangerous unless they are carefully checked before actual publication because of the tendency of many press-services to minimize things of scientific interest and to hunt for the sensational.

Very few stations have a planned program of "public education", that is, lecture-series, visitors' nights, etc. Four stations mention lectures to high schools or clubs, and over the radio. Several stations maintain exhibits of either permanent or timely interest as an aid to handling visitors.

Williams College,
Williamstown, Massachusetts

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30–MAY 3, 1941

SECTION OF METEOROLOGY

REPORTS AND PAPERS

WASHINGTON, D.C.

MAY 1, 1941

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NATIONAL ACADEMY AND RESEARCH COUNCIL BUILDING
9:00 A.M., MAY 1, 1941

METEOROLOGY IN THE 1941 YEARBOOK OF AGRICULTURE

Gove Hambidge

(Abstract)

Back in 1935, Henry A. Wallace, the corn breeder and editor who became Secretary of Agriculture, decided to devote one whole Yearbook of Agriculture to plant and animal genetics. The Yearbook evolved into a series on all the major sciences that are inseparably tied in with modern farming in the United States. The next volume was "Soils and men." Next came the big Yearbook on nutrition called "Food and life." Then we did the current Yearbook, on social and economic problems in agriculture, called "Farmers in a changing world." So we come to the Yearbook on weather and climate in relation to agriculture, which will be called "Climate and man" and will be out sometime in the summer of 1941.

I have been impressed with the fact that each science with which the Yearbook of Agriculture has dealt so far is at the present time in a healthy and vigorous state.

I would be inclined to say that sciences go through alternating periods of stagnation and reinvigoration. Each reinvigoration or renaissance, it seems to me, is due to some great theoretical advance, some fundamental discovery that throws new light on a whole series of phenomena that were previously obscure, and that galvanizes the science with new possibilities of achievement.

Consider the sciences I have named. Genetics at the turn of the century felt the tremendous stimulus of Mendel's discovery of the first simple laws of inheritance. That discovery introduced order into chaos and permitted planned and controlled breeding-work to replace chance. The geneticists knew at once that they could really "go places," and they have been going places, with incalculably important practical results, especially for agriculture.

Soil-science got a similar jolt from the work of the Russian school. These men did far more than originate a useful system of classifying soils. They laid the foundation for a new understanding of any soil anywhere as the product of a total environment which could be studied, analyzed, and to a measurable extent controlled. The old storage-bin idea of the earlier chemists, under which soil-science had been stagnating, was seen to represent only a small part of the truth. Under the new impetus, soil-scientists too could really go places, and they have been busy doing it.

The big jolt in modern nutrition came from discoveries about the role of minerals and vitamins in the animal organism. Most of these discoveries are comparatively recent. You know very well what they mean in the way of improved human well-being. The first wave of the advance was made by the biochemists working with experimental animals. Medical men are now beginning the second big wave of advance, working with human beings. It would be hard to overrate the importance of this newer knowledge of nutrition to mankind.

In the field covered by economics and sociology it is harder to be specific. I wish it were possible to point to some great discovery that gives promise of offering a clean-cut solution for some of our major social problems. There is no question, however, about the existence of a powerful stimulus to thinking and effort in this field; never have they been so intensive because of the sheer pressure of need. If I tried to pin down any particular theoretical aspects of this thinking and effort as having special value, I would say that the institutional economics of the John R. Commons school and the work of the cultural anthropologists promise to be especially significant contributions to an understanding of the modern world.

Finally, in meteorology the big jolt has come from the study of the upper air, which resulted in the polar-front theory and air-mass analysis. This of course is a very recent advance, as recent as the last World War, when the Norwegian school began to reason about the weather vertically because it was shut in from making observations horizontally.

There is a large amount of purely theoretical work still to be done; but so there was after

Mendel's discovery of the simpler laws of inheritance, the first relatively crude formulations of the Russian school of soil-scientists, and the early work with vitamins. Meteorologists now have some confidence that they will be able to bring a wide range of apparently isolated phenomena within the scope of a comparatively few physical laws. The science has received a powerful stimulus to forward movement that even at this early stage is bringing practical results. I would say that meteorology too is on the edge of a renaissance.

Now for a very few words about my subject--meteorology in the Agriculture Yearbook. Like its predecessors in this series of volumes, it tries to cover the full range of the subject, especially in relation to agriculture.

Reichelderfer, Rossby, and Mitchell cover the advances in modern meteorology and their application to daily and longer-range forecasting. Thornthwaite covers the basic world-patterns of vegetation, soils, and agriculture created by climate. Russell reviews the geological and other evidence of climatic change through the ages. Several geographers, including Sauer, Trewartha, Leighly, Stefansson, Broek, deal with the climatic factors that have affected agricultural settlement in the United States and its possessions. A number of soil-conservationists and others write on the flood-problem in relation to climate.

A large section of the book consists of articles by scientists directly concerned with crop-plants, soils, forests, livestock, insects, and diseases of plants and animals. They deal with climate as a major factor in farm-operations; but in spite of the many details covered, they show, consciously or unconsciously, how much is still unknown in this field.

Finally, about half the book consists of detailed tables and maps on climate and weather in the United States, contributed by Kincer and his fellow-workers. The volume of material of this kind seems unduly large, but it was included because we wished to give every farmer in the country as much data as possible about climate and weather in his own neighborhood.

Let me say, however, that I am not in the least interested in publicizing this book with this audience, or persuading you to read it. You are going to read it anyway, or considerable parts of it, because it is in your field. What I wish I could persuade you to do is to read one or more of the books that seem much more remotely related, or entirely unrelated, to your field. The sociologists should read the Yearbook on meteorology; they would learn things they ought to know. You in this audience ought to pick out one of the books on economics, or nutrition, or genetics. You would learn things you ought to know.

This is no frivolous recommendation. The paramount problem in science today, it seems to me, is how to close the gaps between our separate specialties, learn a lot more about each other's work, and discover how science, not as isolated, independent fragments but as a powerful, unified whole, can be focussed on the job of building a decent world.

These Yearbooks of the Department are widely read and used by farmers and students of agriculture. But so far as the scientific specialists themselves are concerned, I am somewhat appalled by the way most of them go for the one book that covers their own field, and casually--sometimes a little scornfully--pass by the others. This is unimportant in itself, but it is one more symbol of a wide-spread habit of mental isolationism. That is more disastrous among scientists than anywhere else, because scientists have supplied the dynamics of modern civilization, and I think they must continue to.

What we need today more than a renaissance in any one science is a good shot of hybrid vigor. And that can only come from much crossing of our very highly inbred lines. I hope the Yearbooks will help to stimulate some of this cross-fertilization.

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THE ZONAL INDEX AND SOLAR ACTIVITY

H. H. Clayton

Atmospheric pressure tends to arrange itself in belts of different intensity encircling the Earth. These belts are well marked in the Southern Hemisphere, but are less marked and are broken in the Northern Hemisphere because of the large continents. Around the equator is a belt of low pressure between latitudes 15° north and 15° south. Between latitudes 20° and 40°, in each Hemisphere, are belts of high pressure; while between 50° and 70° are belts of low pressure, more marked than that around the equator. In the Northern Hemisphere this belt is broken into two segments, one over the North Pacific and one over the North Atlantic.

William Ferrel explained these pressure-belts and the accompanying wind-belts described by Maury as due to the effect of the Earth's rotation on moving air-masses, and showed by computation that theory and observation were in close accord in indicating a maximum pressure near the 30th parallels in both hemispheres, with easterly winds toward the equator and westerly winds in higher latitudes. This deflecting force is now called the Coriolis force by meteorologists.

In order to measure changes in the general circulation of the atmosphere, the meteorologists at the Massachusetts Institute of Technology compute from day to day the mean difference in pressure between 35° north and 55° north and average these differences in five- and seven-day means which they call the "zonal index." Studies of this index in relation to changes of weather in the Northern Hemisphere have been presented in several published reports by these meteorologists [see 1 of "References" at end of paper]. This index is now used in formulating five-day forecasts of weather [2].

In view of this fact, it seemed of interest to compare this zonal index with solar activity as indicated by sunspots. Accordingly weekly values of the zonal index were obtained running from June, 1935, to December, 1938, and compared with sunspot-numbers treated in the same manner. The plotted results for the summer half-year are shown in Figure 1 in which full lines connect the sunspot-numbers and broken lines connect the zonal-index numbers. The small circles show 27-day intervals approximately coinciding with maxima of sunspots.

In April and May of each year there is an inverse relation between sunspots and the zonal index which changes to a direct relation during the summer, although in 1938 this direct relation is only apparent during August and September. In 1935 the direct relation from June to September is well marked. Figure 2 shows a plot of the zonal index and sunspot-numbers for the winter half-year. The curves in this Figure show an inverse relation between the zonal index and the sunspots throughout the period.

The direct relation in summer and inverse relation in winter are clearly brought out by the averages plotted in Figure 3. Taking the minima of sunspots, shown in the plots for each season, and averaging the spot-numbers and the zonal-index numbers occurring simultaneously and for three months before and three months after each sunspot-minimum, results are obtained which are plotted in Figure 5. These plots show that in summer (June to September) low values of the zonal index are found with low sunspot-numbers while in winter high values of the zonal index are found with low sunspot-numbers.

The reason for the inverse relation to sunspots is traceable to the northward movement of the zone of highest pressure with high sunspot-numbers. In Figure 4, the latitude of the zone of highest pressure for each day of January and February, 1937, is shown by the continuous lines, while sunspot-numbers are shown by the dotted lines. From international pressure-charts plotted for the Northern Hemisphere, the pressure was read at each intersection of the 10° lines of latitude and longitude between 20° north and 70° north and an average of the pressure was obtained daily for each latitude.

These averages show that the highest mean pressure is not always found between the 30th and 40th parallels of latitude, but oscillates between low latitudes and high latitudes (70° north or higher). When the sunspots are near normal, the highest pressure is near its normal latitude, but when the sunspots increase greatly in numbers, as they did during the latter part of January and the latter part of February, the position of highest pressure moves to latitude 70° and perhaps covers the entire polar basin. At the same time the pressure falls in middle latitudes. The evidence of this is given in Figures 5 and 6. In Figure 5, it is seen that the pressure during the winter and spring rose and fell at latitude 70° north in unison with the change in the number of sunspots while at latitude 30° north, as shown in Figure 6, the oscillation in pressure was more in line with the inverted sunspot-curve. In other words, the pressure rose at latitude 70° north when the number of sunspots increased and fell at latitude 30° north. This oscillation of pressure between high and low latitudes explains the inversion in the zonal index during the winter and spring.

In the summer when the Sun is shining almost continuously over the polar basin this oscillation between the latitudes is weakened and the normal distribution of pressure from middle latitudes to the pole prevails. These exchanges of pressure between high and low latitudes take place without any appreciable lag in time--not more than a few hours at most. The correlation-

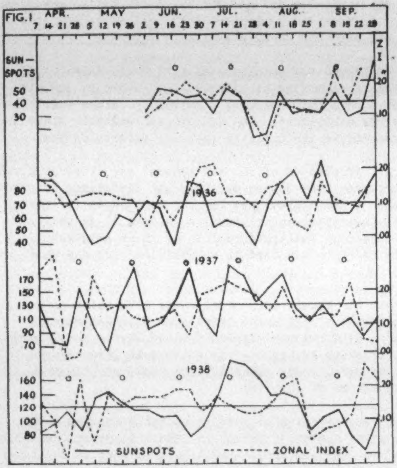
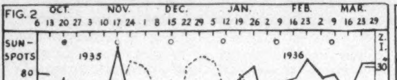


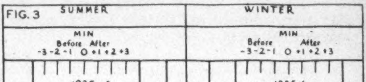
Fig. 1--Sunspots and zonal index, summer half-year, 1935-38

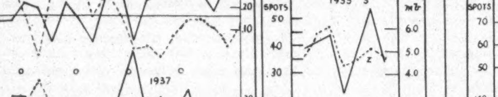
Fig. 2--Sunspots and zonal index, winter half-year, 1935-39

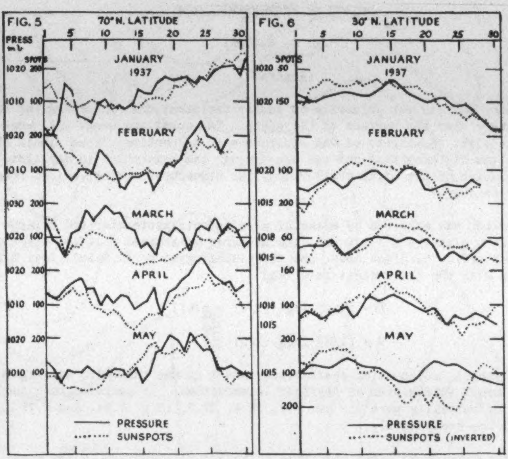
Fig. 3--Mean number of sunspots (S) for each year at times of weekly minima of spots and for three weeks before and after each weekly sunspot-minimum and simultaneous means of zonal-index values (Z), 1935-39

Fig. 4--Latitude of belt of maximum pressure compared with sunspot-numbers, January to February, 1937









Figs. 5 and 6--Sunspots and atmospheric-pressure during winter and spring of 1937

factors between sunspot-numbers and pressure at latitude 70° north for the 151 days from January 1 to May 31, 1937, are: For the same day, 0.67; one day later, 0.59; two days later, 0.46.

Other researches on the relation of atmospheric pressure to solar changes indicate that at least three types of change in pressure follow changes in solar activity:

(1) Air-mass oscillation occurs between low latitudes and high latitudes, the pressure falling in latitudes from the equator to 40° and rising in latitudes above 50°. The greatest fall is between latitudes 30° and 40°, and the greatest rise is at 70° and probably over the entire polar basins.

(2) Air-mass oscillation takes place between continent and ocean, decreasing the pressure over continents with greater solar activity and increasing the pressure over the oceans. In winter this exchange appears to be greatest in high latitudes and in summer over low latitudes.

(3) Wave-motions are set up as a result of air circulation around areas of low pressure acted upon by the increase of the Coriolis force with increased latitude. These waves in general travel from west to east.

The causes of these air-mass exchanges appear to lie in the following facts: (1) Insolation exceeds radiation south of 45° latitude, while north of that latitude radiation exceeds insolation; (2) heating by insolation is greater over land-surfaces than over water-surfaces; (3) snow-surfaces are the most effective radiating surfaces; (4) owing to the effect of the Earth's rotation, pressure-changes increase in intensity with increase of latitude, approximately as one divided by the cosine of the latitude; (5) when solar activity increases the changes in atmospheric pressure on the Earth indicate that air-mass movement takes place from regions where insolation is greater toward regions where it is less, more especially toward regions where radiation exceeds insolation.

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Canton, Massachusetts

OPTICS OF ATMOSPHERIC HAZE

E. O. Hulburt

(Abstract)

Experiments were carried out primarily to answer two questions concerning the optical properties of the atmosphere near the surface of the earth. The questions were: (A) What is the attenuation for white light (daylight) of the atmosphere as a function of the visual range, the visual range being the distance that one can see through the atmosphere in daylight; (B) what is the angular distribution of the light scattered by the atmosphere during various conditions ranging from clear to foggy?

The first question was answered by means of a telescopic photometer and a large approximately black body at a distance $d = 3.2$ km. The measured brightness b of the black body and h of the horizon sky just above the black body, and the visual range v for values from 3.2 to 15 km were found to agree with the theoretical relations

$$\beta = (1/d) \log_\epsilon [1/(1 - b/h)]$$

and

$$V = (1/\beta) \log_\epsilon (1/\eta)$$

where β is the atmospheric attenuation-coefficient, and η is the threshold of brightness contrast being 0.02 for the usual intensities of daylight illumination. It followed that the ratio of β to the attenuation of optically pure air was 277, 55.4, 27.7, 13.8, 5.54, and 2.77 for $V = 1$, 5, 10, 20, 50, and 100 km, respectively.

The angular distribution of light scattered by haze was determined in two ways: (1) By measuring the brightness at various angles of a searchlight-beam at night and (b) by measuring the brightness of the horizon-sky at various azimuths for a moderately low Sun and a cloudless sky. The distribution was much the same for haze ranging from thin to thick. It showed pronounced forward scattering, over three-fourths of the light being scattered in a forward direction and less than one-fourth in a backward direction. Such a scattering distribution would occur from haze-particles of various sizes, most of them being of dimensions greater than the wave-lengths of white light.

[The complete paper will appear in the Journal of the Optical Society of America, v. 31, pp. 467-476, 1941.]

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ATMOSPHERIC-PRESSURE WAVES NEAR PASADENA

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(Contribution 312, Balch Graduate School of the Geological Sciences,
California Institute of Technology)

In a previous paper [see 1 of "References" at end of paper] the authors have described results obtained from records of electromagnetic microbarographs. These experiments have been continued, and special interest has been given to the rather regular waves with periods of usually 2 to 5 seconds, which have been called "microbaroms" in the earlier paper. In January, 1940, a barograph with a larger loudspeaker-element was installed at point 2a, Figure 1, and connected with a galvanometer, constructed by F. Lehner, at the Seismological Laboratory, having a free period of about 1/2 second. This instrument has recorded regularly on a drum with a speed of one mm per second. The older two instruments were connected with Lehner galvanometers and remained at points 1 and 2a, respectively. Records were taken at irregular intervals with various speeds of recording, up to five cm per second. In December, 1940, a third instrument of this type was added. Figure 2a was taken with the three instruments side by side and shows that their characteristics were alike within small limits. From December 26, 1940, to March 31, 1941, the three instruments were located at the points 1, 2b, and 3 of Figure 1, respectively, and recorded usually twice every day for about one hour with a speed of three mm per second. Figures 2b, 2c, and 2d show examples of the records. The distances are as follows: 1 to 2a, 130 meters (426 feet); 1 to 2b, 320 meters (1,050 feet); 2b to 3, 290 meters (950 feet); 3 to 1, 264 meters (865 feet). Instruments 1 and 3 are in dense shrubs under high trees; instrument 2b is under

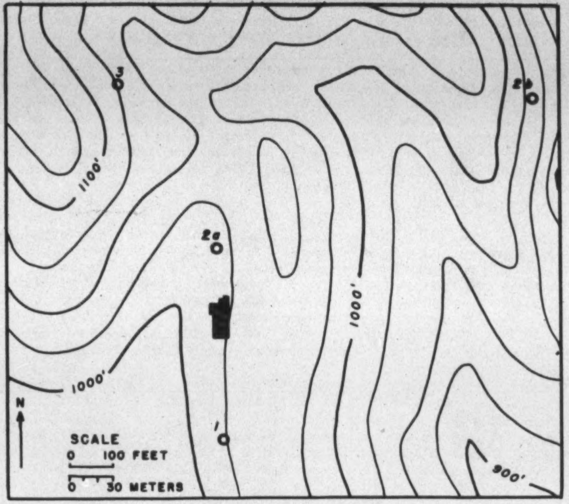
3
2b
1100'
2a
1000'
1000'
1
900'
N
SCALE
0 100 FEET
0 30 METERS

Fig. 1--Location of barographs

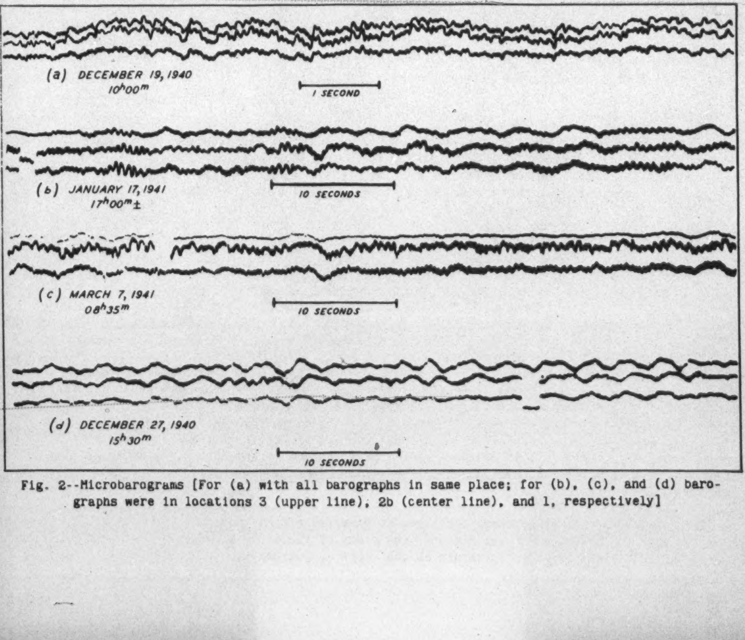

Fig. 2--Microbarograms [For (a) with all barographs in same place; for (b), (c), and (d) barographs were in locations 3 (upper line), 2b (center line), and 1, respectively] small shrubs without trees. In general, the records of instrument 2b were much more frequently disturbed by wind than those of the other two. Besides, during the day and sometimes at night, there appear to be more or less regular air-currents up or down the slope near 2b.

The following are results found from the records: The microbaroms are very small during the summer. About the beginning of September, they begin to increase, reach their maximum during the winter and die down rather rapidly during March. During the three months when all three instruments were operating, there was never a time-difference of more than a small fraction of a second between the records of instruments 1 and 3, whereas 2 always received the waves later by almost one second (see Figs. 2b-2d). Consequently, the waves came from southwest to west (calculated azimuths between 230° and 270°. The waves arrive almost horizontally, but this is to be expected, even if the source is at some distance in the lower stratosphere, due to the curvature of the rays convex to the ground.

In all instances, where the amplitudes were unusually large, a rather pronounced low-pressure area was situated off the coast of Southern California. As soon as the low-pressure area passed the coast, the microbaroms decreased rapidly. During the months January to March, 1940, the microbaroms were much smaller than in the corresponding months in 1941, when low-pressure areas were much more frequently close to Pasadena than in 1940. No correlation was found with microseisms. On the contrary, the microseisms are a phenomenon not related to local conditions. On the other hand, both show the same type of yearly period and similar relationship to low-pressure areas, one locally, the other with distant storms; consequently, a similar type of source seems to be indicated.

Microbaroms have been found, in the interim, by Baird and Banwell [2] at Christchurch. Their findings correspond in every respect with the results obtained at Pasadena. They believe that microbaroms and microseisms are independent phenomena, possibly both related to large swells. Large ocean-waves in storms are not excluded as source of the microbaroms at Pasadena, though on relatively calm days when large swells break on the nearest coast the microbaroms remain small.

Other results presented in the previous paper [1] were confirmed. Trains of short waves were found again in a few instances. On January 17, 1941 (Fig. 2b), they came from the same direction (west-southwest) as the microbaroms. On other days, the amplitudes were too small to correlate the three records. On some days, vibrations with periods of a small fraction of a second were observed (Fig. 2a, 2c), but it could not be decided whether they are pressure-waves. Finally, the convection-currents gave practically the same records as in the preceding years.

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APPARENT RATE OF PROGRESS AS AFFECTED BY CHANGING INTENSITY OF HURRICANE SAN FELIPE (II) WHILE CROSSING PUERTO RICO

Charles F. Brooks

On R. G. Stone's map [Trans. Amer. Geophys. Union 1941, p. 254, 1941] of isochrones of lowest station-pressure as the great hurricane of September 13, 1928, crossed the length of Puerto Rico there is an apparent acceleration in the advance of the storm in the east portion of the Island and a retardation in the west. In such a major storm, which must have reached great heights and been carried along, therefore, by the average of the winds through that deep portion of the atmosphere penetrated, it does not seem likely that a disturbance of its lower part by friction with a moderately mountainous island could have materially changed the general rate of progress of the storm.

If uniform progress is assumed, the times of observed minimum pressure can be compared with the times when the storm-center was nearest, and a map of the differences can be prepared. Using Stone's map, the times of lowest pressure as the storm approached the Island and after it had

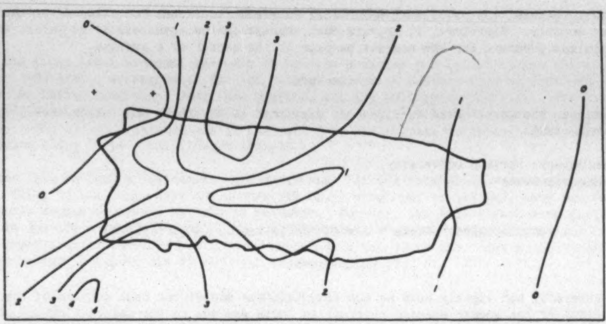

Fig. 1--Advance of time of minimum pressure ahead of time of probable passage of center of hurricane of September 13, 1928, across Puerto Rico (Units are in hours; in northwest corner minimum pressure came after passage of center and in rest of Island before)

left, namely, 1 p.m. and 11 p.m., lie on lines 135 miles apart. When the space between these lines is divided into ten hourly units of 13.5 miles each,we should have the approximate hour-by-hour advance of the storm. Subtracting the observed times of lowest pressure as shown by Stone's map over and near the Island from these assumed times of steady advance, we arrive at a map shown as Figure 1.

As the storm came ashore at the east end of the Island, the minimum pressure occurred an hour before the arrival of the center. Before the axis reached the central longitudes of Puerto Rico the advance of the minimum pressure was a matter of two hours on the northern and southern lower lands, but still only an hour on the mountains. Still farther west, the advance of the minimum pressure exceeded three hours. On the west end, however, as the center moved out to sea the time of minimum pressure quickly approached the time of storm-passage, and on the extreme northwest corner even came after the center had passed nearest.

The lowest pressure observed when the storm came ashore was 27.30 inches; the minimum, as the storm was leaving the Island, had risen to 28.46 inches. The central pressure thus rose more than one inch in the 5-1/4 hours. This rise was evidently caused by the effect of friction in reducing the velocity of the whirl and consequently the centrifugal force that helped to maintain its low pressure. After the storm left Puerto Rico and continued on toward West Palm Beach and Lake Okeechobee, Florida, it recovered its strength soon, and on the next day had a minimum pressure of 27.80 inches and on the second day of 27.43 inches, at West Palm Beach [1].

We can now see why the minimum pressure at a station in Puerto Rico should come before the storm-center was nearest--as the storm was filling up over the Island the pressure at the center was rising faster than the nearer approach of the center could bring lower pressures to the station. In other words, the isobars were moving toward the center in advance of the storm faster than the storm was moving forward.

The earliness of the minimum pressure, one to three hours, was greater where the whirl was most hindered by the general roughness of the Island, namely, the lower elevations. At the height of the tops of the mountains, however, the rotation was not obstructed so much, and the advance in the time of minimum pressure was of the order of only one hour. At the west end of the Island when the hurricane regained the sea its system of isobars began moving outward rapidly as it deepened, and so rapidly that the pressure continued to fall, though not for as much as an hour, after the center had been nearest.

Thus, if the time of lowest pressure is used as a criterion of the advance of the storm, the center will appear to advance rapidly as the land is reached, and it will seem to linger as the storm goes out to sea.

That this is a general rule has been found by a tabulation of 15 hurricanes on the Gulf and southern Atlantic coasts, the details of which will be presented in the Bulletin of the American Meteorological Society. Therefore, it appears that, except in the open sea, it is unsafe to use the time of minimum pressure for the nearest passage of the center of a cyclone.

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FORESHADOWING MONTANA'S WINTER PRECIPITATION (VERIFICATION)

I. I. Schell

(1) It was generally but vaguely held at one time that the modest but real success of the official predictions of the summer monsoon-rainfall in India was due to the peculiar nature of the monsoon. However, it appears from Walker's studies and from the fact that seasonal foreshadowing has been adopted by the official services of several other countries that, as far as it can be shown, the principles on which the predictions of monsoons are based evolve from the apparent fact that the rainfall of India during monsoon, like the winter precipitation of northwest central North America, for example, is but one of a substantial number of elements which have the property of being components of several interconnected relationships which go by the name of Oscillations [see 1 of "References" at end of paper]. (The term "foreshadowing" as applied to predictions of the seasonal weather was introduced by Walker to denote the difference between the rather detailed daily forecast and the seasonal forecast, which is given in more general terms; the term refers to forecasting the "weather-trend," and is thus akin to the term "Witterungsvorhersage" adopted by Baur.)

The Oscillation of particular interest to this country and Canada is the Southern Oscillation of September to November since, as was shown by Walker and Bliss [2], there is an apparent relationship between its activity and the trend of the precipitation during the following winter in Montana, Idaho, Wyoming, Manitoba, Saskatchewan, and Alberta--an area of roughly a million square miles. There appears to be also a similar relationship with the winter precipitation in Florida and the Bahamas.

The Southern Oscillation of September to November represents an interconnected relationship between pressures in the area of southeast Asia to north Australia as represented by the stations Manila, Port Darwin, Batavia, and a group in northwest India, and temperatures at Auckland and Batavia, and rainfall in Java. Thus there are seven elements which comprise the Oscillation. The average number of years on which the correlations of the interconnection were based is 56, the lowest being 47. The values of the correlation-coefficients of the individual centers with the Oscillation as a whole range from 0.6 for temperature at Batavia to 0.9 for pressure at Port Darwin.

The relationship between the Southern Oscillation of September to November and the following winter precipitation in Montana was studied further [3] with the view of determining whether or not the relationship will hold reasonably also for years not included in any arbitrarily chosen period on which it may be based, and thus serve as a basis for future foreshadowing. The method used [4] consisted of breaking up the available 44-year period of data (1895/6-1938/9) into a period of 33 years, on which a formula is based, and a period of 11 years used as a test; this was performed four times, permitting the derivation of four formulas each based on a period of 33 years, and allowing a test of four successive 11-year periods not included in the formulas, and hence of the entire 44 years. The computed departures derived with the aid of the respective formulas favorably agreed with the actual departures, both with respect to sign and amount of departure [3]. A further analysis also led to a revision of the Southern Oscillation in so far as its relationship with Montana is concerned. The Java rainfall and Batavia temperatures were both dropped, and, for practical considerations, the stations in northwest India were substituted by Calcutta. For physical reasons it was further decided to treat the four pressure-elements as a unit.

In conclusion, the experiments with the relationship between the Southern Oscillation of September to November and the following winter precipitation in Montana indicated that there is a reasonably good chance that future predictions of Montana's winter precipitation based on the activity of the Southern Oscillation of September to November will verify with a degree of accuracy appreciably greater than that expected by chance.

(2) The first trial seasonal forecast of Montana's winter precipitation was attempted for the winter 1939-1940. Arrangements for the receipt of cabled weather-reports were made at Blue Hill with the India, Australia, Java, New Zealand, and the Philippine services. The cabled reports revealed "no basis ror expecting an important departure" [5] in the winter precipitation of Montana. The actual departure was 18 per cent [6], the average departure of Montana's winter precipitation being 20 per cent (1895/6-1938/9).

In the fall of 1940 preparations were again made for the receipt of overseas cables on weather. Owing to the censorship and consequent delay grown out of the War, only two (out of five) reports became available by late in December. However, the indications were sufficiently definite to justify a prediction of a "defect" in Montana's winter precipitation [6]. The additional reports which subsequently arrived agreed with the first two. The actual precipitation during the winter 1940-1941 was 47 per cent of the average [7].

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THE CHEMICAL ABSORPTION HYGROMETER AS A METEOROLOGICAL INSTRUMENT

C. W. Thornthwaite

In the Monthly Weather Review for January 1939 the author in collaboration with Benjamin Holzman [see 5 of "References" at end of paper] reported on a new method for measuring evaporation from land- and water-surfaces. The method involves recent developments in aerodynamics and employs the general equation

$$E = - A\ (dq/dz) \qquad (1)$$

in which A is the intensity of turbulent mixing or the Austausch-coefficient and (dq/dz) is the rate of change of concentration of atmospheric moisture with respect to height.

Meteorological observations required for the determination of evaporation are wind-velocity and humidity at two levels, the two wind-velocities for determining the intensity of turbulent mixing, and the humidity-measurements for securing the moisture-gradients. In terms of these observations the evaporation from a natural surface may be expressed as

$$E = K_0^2\ \rho\ (q_1 - q_2)(u_2 - u_1)/[\log_e\ (z_2/z_1)]^2 \qquad (2)$$

in which K_0 is the universal turbulence constant, ρ is the density of the air, q_1 and q_2 are specific humidity of the air at the lower and upper levels, u_1 and u_2 are wind-velocities at the lower and upper levels, and z_1 and z_2 are heights of the lower and upper points of observation above the base of the turbulent layer.

In the original installation at Arlington Experimental Farm the wind-velocity measurements were made with standard Soil Conservation Service type three-cup anemometers and the moisture-measurements with Soil Conservation Service type hygrothermographs. The station was kept in operation throughout 1939 and a nearly complete hourly record of evaporation and condensation from the field was obtained for the year. Monthly summaries were reported to the Hydrology Section of the American Geophysical Union a year ago and are published in the Transactions [6].

It was pointed out in the original report that the hair-hygrometer possesses serious defects, the chief being its tendency to drift out of calibration. To minimize errors due to this tendency the instruments were calibrated in pairs and two pairs were required for each station. While the actual records were being obtained with one pair of instruments, the other pair was being calibrated in a constant-humidity chamber. The instruments were changed each week. Although reliable results were obtained in this manner from the hygrothermographs, the labor and difficulty of calibration precluded the wide-spread use of the method.

The objective of our evaporation-study is to develop a new type of climatic data--namely, evaporation from the natural land-surface--and to secure these data for many different types of areas in the various parts of the country. With the goal of establishing perhaps hundreds of evaporation-stations in the near future, it became evident that the cost of installation and operation would have to be reduced to a minimum. Thus, it was realized that the use of hygrothermographs, involving a high initial cost and requiring constant surveillance and frequent recalibrations, would not permit the establishment of the number of stations desired. Consequently, other possible methods of measuring atmospheric humidity have been examined.

Four distinctly different methods of determining atmospheric moisture are in regular use: (1) The chemical absorption-method; (2) the temperature of condensation, or dew-point method; (3) the wet- and dry-bulb psychrometer-method; and (4) the hygroscopic expansion-method. All are well known and will not be described here [2, 3].

The chemical absorption-method has generally been regarded as a laboratory technique, not adapted to field-use. Spilhaus [4] dismissed it entirely with the statement that it "may be eliminated as impractical for obvious reasons." A measured volume of air is passed through tubes containing a desiccating material and the water absorbed from the air is measured, usually as a gain in weight of the tubes during a designated period of time. Under favorable conditions the average absolute humidity as an integrated value for the period of a day can be determined to within 0.1 per cent of its true value. The method is of no value for the determination of the moisture-concentration in the air at any given moment.

For use in hydrologic and climatic investigations, measurements of evaporation need not be made for time intervals of less than one day. Thus, a method of determining atmospheric moisture as an integrated value over a period of considerable length would be more useful than one which gives a continuous record of the momentary conditions of moisture-concentration. For this reason the chemical absorption-method is especially attractive. Another virtue is that the original evaporation-equation becomes further simplified by the substitution of absolute humidity-values for vapor-pressure or specific humidity.

The difficulty with the method for field-use involves the measurement of the volume of air passed through the tubes. The customary laboratory procedure of allowing the air to displace a given volume of a liquid as it flows from a closed container is not adapted to field-use. On the other hand, pumps that will deliver air at the rate of five to ten liters per hour with the necessary accuracy were not available. This report describes the steps in the evolution of such a pump.

By adapting the principle of the Geissler-Toepler air-pump, a small dual pump having the needed capacity was designed and built. The essential element of the pump is a horseshoe-shaped glass tube, open at both ends and partly filled with mercury. A rocking motion of the tube causes the mercury to move back and forth from one end to the other, alternately forcing the air out and drawing it in. Since the total volume of the tube is constant, the amount of air entering one end exactly equals that being forced out of the other. Equipped with suitable valves, both ends of the tube become individual pumps identical in capacity.

The pump was first driven by a small 110-volt alternating-current motor. Later it was found that a direct-current motor, designed for the United States Coast Guard to operate for an entire year from a single 6-volt dry-battery, has ample power to drive the mercury pump, and a second instrument was built using this motor. It was much more adaptable to field-use than the first because it was independent of a source of power.

A chemical absorption-apparatus using this pump was installed in the field at Arlington on

November 1, 1940, and was operated successfully until the middle of December, during which time reasonable daily values of evaporation and condensation were obtained. It was mounted at the base of a standard wind-tower and air was drawn down from the 4-foot and 16-foot levels through 1/4-inch copper tubing, the samples being taken exactly in the horizontal planes where wind-velocities are determined. In order to exclude dust, rain, and insects the ends of the tubes were bent downward and were fitted with copper wool-filters. The indicators for wind-mileage at the two levels were mounted above. Although evaporation-measurements were not made after the middle of December, the pump continued to run without interruption until April 1, when it was dismantled.

An improved device, using two glass hypodermic syringes as pump cylinders and pistons and with diaphragm-valves, driven as before by the constant-speed, battery-operated motor, was received in February 1941. For summer and winter operation, this pump-unit will draw accurately 4.5 or 9.0 liters of air per hour through the absorptive apparatus from each of the two levels.

In late March an apparatus using but a single pump and taking air-samples alternately from the upper and lower levels was received. Although the instrument has not yet been adequately tested, it promises to provide an accurate means of measuring atmospheric moisture and will permit the establishment of simple and inexpensive evaporation-stations.

The chemical-absorption hygrometer requires a suitable drying agent. Such an agent should remove all of the water-vapor from the air and should have a large water-holding capacity. It should be granular to allow an unimpeded flow of air through it. It should be capable of reactivation so that it can be used repeatedly, and should be safe to handle in the field as well as in the laboratory. These latter requirements eliminated the otherwise efficient phosphorus pentoxide (P_2O_5) and sulphuric acid (H_2SO_4).

After examining the results of tests on a number of drying agents by Bower [1] at the National Bureau of Standards, alumina (Al_2O_3) was selected as being the one most nearly meeting the requirements. It is convenient to use, is perfectly safe, can be easily reactivated, and is relatively inexpensive. Alumina will hold nearly 20 per cent of its weight of water and leaves only 0.005 milligram of residual water in each liter of air.

Alumina depends for its efficiency not only upon absorption but on adsorption as well. Absorption is a chemical process and results in the chemical combination of water-molecules with the Al_2O_3 molecules. Adsorption is merely a physical process in which molecules of water adhere to the surface of the drying agent. To increase the adsorptive efficiency of the alumina, it is specially prepared as a colloidal gel by which means its surface-area is enormously increased.

Alumina will adsorb carbon dioxide from the air in small amounts. However, it quickly reaches equilibrium with the concentration of carbon dioxide in the air, so it can be saturated with carbon dioxide without reducing its capacity for water, by passing a few liters of dry air through the tubes before they are used.

Standard U-shaped glass drying tubes are used to hold the drying agent. The tubes each have two glass sidearms to facilitate making the necessary connections to the pumps and the sampling tubes. They also have ground-glass stoppers for sealing when samples are not being taken. Only by coating the stoppers with a thin film of petcock-grease can all leakage be prevented. Unless this precaution is taken the alumina will pick up as much as one milligram of water per day.

In order to achieve the desired accuracy, great care must be exercised in the weighing of the drying tubes. An analytic balance sensitive to 0.00005 gram in 100 grams is needed and standard laboratory procedures should be employed.

As long as both pumps draw exactly the same amount of air from both levels in a given time-interval, most of these possible errors are neutralized when absolute humidity-gradients are determined. The mean value of the absolute humidity-gradient for a given length of time is obtained by dividing the difference in mass of water-vapor collected from the two levels by the volume of air drawn through each tube.

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ERRORS IN MEASUREMENTS OF CONDENSATION-NUCLEI

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One may be interested in measurements of the concentration of the nuclei of condensation in the atmosphere for one or more of the following reasons: (a) Because of the fundamental role of these nuclei in the formation of fog and clouds; (b) because of their relation to the pollution and the visibility of the atmosphere; (c) because of certain associations of these nuclei with other meteorological phenomena, such as type of air-mass; and (d) because of the marked influence they exert in the phenomena of atmospheric electricity. In any case, one will need, sooner or later, an estimate of the reliability of nuclei-counts.

A consideration of the error in nuclei-counts is more important than is the case in many measurements in meteorology because, quite apart from errors which may arise from technical imperfections, there is a minimum standard error which for the mean of ten counts is generally of the order of ten per cent and can be reduced only by increasing the number of counts. The source of this will be seen when certain essential features of the method of counting the nuclei is recalled.

Briefly, that method is as follows: A small sample of air containing nuclei is admitted into an expansion-chamber where it is mixed with air which is free from nuclei and saturated with water-vapor. Then when the air is suddenly expanded, water-vapor condenses on the nuclei. The small droplets thus formed fall and those in a restricted column settle upon a counting stage. Obviously the number which is counted will vary from sample to sample according to some law of probability, even though the count is correct and the samples are all taken from the same parent population. In order to intelligently discuss the significance of results one often needs to know the form of that law.

From theoretical considerations Scrase [see 1 of "References" at end of paper] showed that these counts should be distributed according to the Poisson law of probability, namely

$$Y = N\, e^{-\mu} \mu^{X}/X!$$

where (Y/N) is the probability of the occurrence of a certain count X and μ is the mean of all N counts where N is large. An important feature of this law is that the variance (square of the standard deviation σ) is equal to the mean or $\sigma^2 = \mu$.

Although Scrase felt that his data were fairly consistent with this law, he did note what seemed to be a small but apparently significant departure. Sherman [2], from a comparison of the variance with the mean, found a similar departure, namely, that the actual variance is less than the mean and therefore less than that for a Poisson distribution.

The frequency-distribution for a portion of the data discussed by Scrase is shown in Figure 1. This is for the counts on 100 samples, the mean count being 4.0 and the variance 2.9. Obviously the variance is much too small to satisfy a Poisson distribution. The appropriate Poisson distribution (mean or variance = 4) is represented by the broken curve. The full-line curve in Figure 1 represents a normal distribution for which the mean and variance are those of the actual data.

It is indeed surprising to find that these values for the variance are so much less than the mean count. In the first place, the samples cannot generally be regarded as coming from the same parent population. There is much evidence to show that the concentration of the nuclei in the atmosphere varies considerably with time, which of course should tend to increase the variance for any set of samples, even though--as was done by both Scrase and Sherman--the measurements studied in this respect were selected with a view toward avoiding changes in the parent population.

Scrase thought that the observed departure "may be due to the tendency for the observer to reject a low count at the beginning of an observation on the suspicion that the expansion may not have been effective." Such a conjecture seems inadmissible for data with which this report is concerned because a considerable number of sets of counts were obtained in succession each day and the mean count is about ten. In conversation Sherman raised the question whether the departure from the Poisson law may have been introduced by the selection which was made for the purpose of avoiding fluctuations in the average concentration of nuclei.

That source of uncertainty in the conclusions is avoided in the present investigation by using a form of the "chi-square" test for the validity of a Poisson distribution. This test is based on the fact that in a Poisson frequency-distribution the variance (σ^2) of a large set of measurements should be equal to the mean value (μ), or (σ^2/μ) = 1. For a set of samples taken in rapid succession the parent populations from which these are taken may be expected to differ less than in a set which is collected at intervals over a greater period of time, and therefore in the average the ratio $(1/n)\ \Sigma\,(S_n^2/N_n)$--an estimate of ($\sigma^2/\mu$)--derived from a number of short series should be less dependent upon the variation of the parent population than the corresponding ratio derived from larger subdivisions or from all of the same data. Accordingly the former, "internal," index should be smaller than the "external index," which in this study is the variance with respect to the mean of all the data of a given category divided by that mean.

A histogram derived from the counts on 900 unselected samples is shown in Figure 2. The overall mean of these counts is 13.9 and the corresponding variance is 24.0. That a ratio of variance to mean as great as this (1.73) was found only rarely for sets of ten successive measurements is shown by the histogram in Figure 3 where only eight out of 268 values of the "internal" index equal or exceed 1.7, and the mean is 0.79. This contrast in values seems definitely attributable to an increase of the external index owing to variations in the average concentration of nuclei. In ordinary practice a greater contrast would doubtless be found because in the present work the counts were made in a closed room where the concentration of nuclei, and also its variation, was doubtless less than is usual about cities.

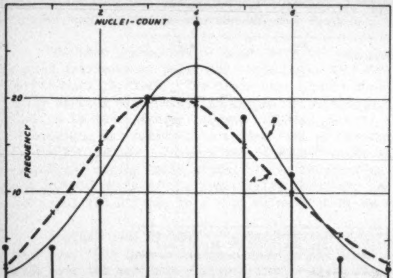
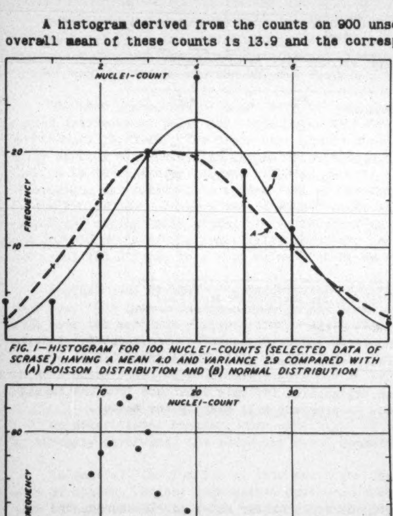


FIG. 1—HISTOGRAM FOR 100 NUCLEI-COUNTS (SELECTED DATA OF SCRASE) HAVING A MEAN 4.0 AND VARIANCE 2.9 COMPARED WITH (A) POISSON DISTRIBUTION AND (B) NORMAL DISTRIBUTION



On the assumption that the Poisson distribution applies to these data, the histogram in Figure 3 should be a chi-square distribution with nine degrees of freedom [3]; however, it is a close fit to a chi-square distribution with eight degrees of freedom. It is probably a coincidence that the fit is so close to a particular chi-square distribution because, as already noted, the parent population was not constant and one would expect this to be reflected in somewhat enlarged values of the internal index.

Evidence that the internal index is somewhat dependent upon variations of the parent population seems to be indicated by the correlation between the internal (K_1) and the external (K_e) index, shown graphically in Figure 4. The regression of K_1 on K_e is given by the relation $K_1 = 0.23\ K_e + 0.50$. This was derived from 27 pairs of values, each value being derived from the counts made on about 120 samples. Thus a value of K_1 is the variance about the mean of about 120 counts divided by that mean and K_1 is the mean of about 12 values each of which was derived from a set of ten successive nuclei-counts. The highly significant correlation ($r = 0.75$) shows that even under rather favorable conditions there is often sufficient variation in the average concentration of nuclei in air to appreciably affect the variance in counts on ten successive samples.

One may infer from this relation between K_1 and K_e that when the parent population is invariable the value of K_1 is less than the mean value (0.79). Indeed, it seems admissible to infer from this relation that $K_1 \overset{\equiv}{<} 0.73$, the value which corresponds to $K_e = 1$ and which is also close to the median of the distribution of K_1.

The conclusion is reached that with the equipment and technique used in this investigation a modification of the Poisson type of distribution or some other distribution is required, but whatever the distribution the variance of ten successive counts about the mean count for samples from a common population is in the average not more than 70 per cent of the mean.

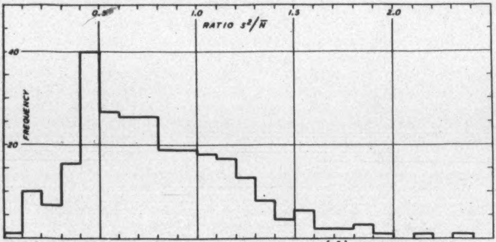


FIG. 3—HISTOGRAM OF RATIO OF INTERNAL VARIANCE (s_n^2) TO MEAN NUCLEI-COUNT ($\bar{N}_n$) FOR EACH OF 267 SETS OF 10 SAMPLES EACH (OBSERVATIONS BY M.L.P.)

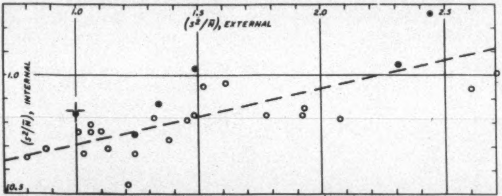


FIG. 4—CORRELATION OF INTERNAL WITH EXTERNAL ($s^2/\bar{N}$) FOR 28 GROUPS OF ABOUT 120 SAMPLES EACH (OPEN CIRCLES FOR OBSERVATIONS BY M.L.P., ALL MADE IN A CLOSED LABORATORY ROOM; OTHER OBSERVATIONS MADE OUT OF DOORS)

The writers are not yet ready to advance an explanation for this departure from the expected distribution, but hope that investigations now in progress will clarify the matter.

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STATUS OF OZONE MEASUREMENTS AT NEW YORK CITY

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Since the beginning of 1941 measurements of the amount of ozone in the atmosphere have been made almost daily at New York University. The instrument used is a photoelectric spectrophotometer designed and calibrated by Dr. G. M. B. Dobson [see 1 of "References" at end of paper] in England, and obtained by means of a generous grant made by the Research Corporation of New York City for the purpose. The amount of ozone in the atmosphere is determined by comparing absorption by the atmosphere of radiation from the Sun of wave-lengths 3110 Å and 3300 Å. The shorter wave-length is more strongly absorbed by ozone and thus from measurements of the relative intensities of these wave-lengths received at the Earth's surface the amount of ozone in unit vertical column of the atmosphere may be calculated. This is usually expressed in centimeters of ozone gas at normal temperature and pressure. In the instrument provision has also been made for measurement of the intensity of a third wave-length of 4450 Å which, in connection with the other wave-lengths, permits measurements using light from the cloudy zenith-sky, an attribute which is quite valuable during periods of cloudy weather.

In the computation of the amount of ozone the effect on light of scattering by air-molecules and "small" particles must, of course, be considered. The wave-lengths used by this instrument are near enough together that variations in the amount of haze ordinarily do not have a marked differential effect on them. For the computations a formula of Dr. Dobson's involving a constant correction for the effect of haze and molecular scattering has been used. However, a considerable amount of haze or smoke is often present over New York and there is some question as to whether this assumption always obtains. Although there is thus some doubt as to the validity of small variations in amounts calculated in this way, changes of haziness cannot, of course, obscure the large changes of ozone.

Ozone varies irregularly from day to day and numerous investigators have found relations between total ozone and corresponding meteorological conditions. A few major fluctuations which occurred during the period of observations which appear to be especially well related to the current weather may be of interest.

The most pronounced of these were the sharp rises and the high values of ozone which accompanied outbreaks of polar air, especially in February and March. One good example of this was on February 19, 1941. The ozone rose almost steadily from 0.26 cm on February 15 until in the early morning of February 19 it had reached 0.40 cm. By $10^h 30^m$ it was 0.44 cm, dropping off to 0.43 cm by 13^h. A deep low was situated east of the New England area with an intense, cold high influencing the temperature as far east as New York even though centered northwest of the Dakotas in western Canada. Isobars were closely packed all through the eastern United States with accompanying strong north winds. It is interesting to note that the high center did not move east and that in spite of the practically identical surface pressure-distribution of the next morning the ozone had dropped to a noon value of 0.31 cm (Fig. 1).

Another good example of a sharp outbreak of this type was on March 17. Again there was a deep low, this time centered somewhere north and east of the New York Area, with a strong cold high over the northern Plains States. Again there were the strong winds, with gusts up to 60 mph measured at New York University. The ozone rose from 0.30 cm on March 14 to 0.36 cm the morning of March 17, then rising rapidly reached a maximum of 0.45 cm later in the day (Fig. 2). In both these cases intermediate values are in line with and substantiate the sharp maxima reached.

At other times, however, when conditions on the surface-map have been similar, although not so strongly developed, the ozone has shown no marked variation.

In general, the results of this short period of investigation appear to be in line with the work of others. Rather high values have been observed but at a time of year when other investigations have shown a maximum. January had the lowest values and March the highest; this is in accord with the seasonal trends observed elsewhere. As a period of low pressure passes there is usually a tendency for the ozone to increase. There appears also to be some correlation with the height of the tropopause (Fig. 3).

The question of the effect of smoke and haze on the measurements is important. If satisfactory measurements can be made under adverse conditions of smoke and haze it will facilitate the building up of a network of stations as these may then be located where large establishments are normally maintained.

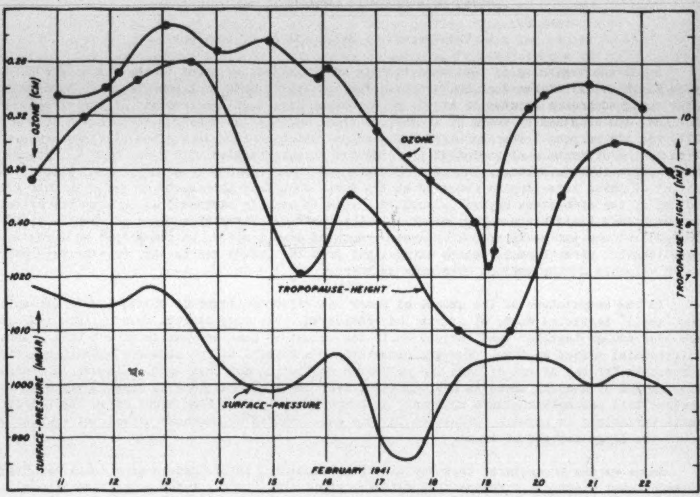

Fig. 1--Ozone, tropopause-height, and surface-pressure at New York

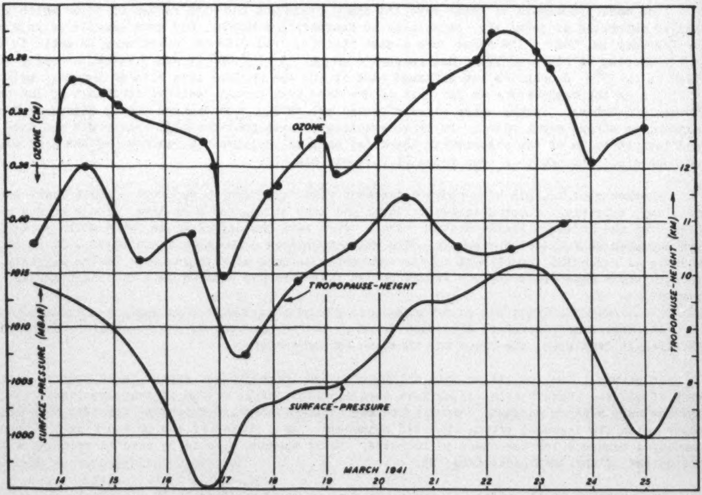

Fig. 2--Ozone, tropopause-height, and surface-pressure at New York

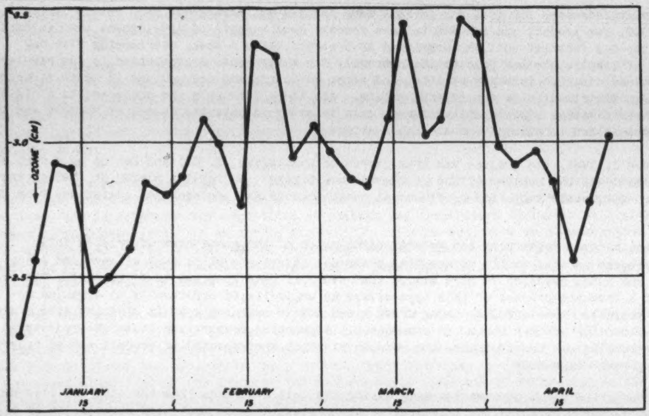

Fig. 3--Mean ozone values at New York for 5-day periods (periods as in zonal-index means)

With the fine radiosonde network, which already exists, we have a unique opportunity of studying the meteorological implications of atmospheric ozone if a number of stations can be established.

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COMMENTS ON THE WEATHER BUREAU'S EXPERIMENT IN FIVE-DAY WEATHER-FORECASTING

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(Summary)

In the summer of 1936 the United States Department of Agriculture in cooperation with the Massachusetts Institute of Technology organized a cooperative research-project, the broad purposes of which were, first, to arrive at a clear understanding of the atmosphere as a thermodynamic circulation-engine, secondly, on the basis of such a satisfactory model for the general circulation of the atmosphere, to develop a technique for five- to ten-day forecasting of weather, with particular emphasis on the forecasting of the geographic distribution of five- and ten-day anomalies of temperature and rainfall over the United States.

In the course of these investigations considerable progress was made with the description and interpretation of circulation-patterns in summer over the continent of North America. The development of isentropic analysis was the first important specific practical result of this research. Later, efforts were concentrated on the interpretation of the circulation in winter in the Northern Hemisphere. In the course of this phase of the investigation important, slow irregular changes in the cellular structure of the atmosphere were discovered and a preliminary dynamic theory for these changes was formulated, which already has proven its practical value as a tool in five-day forecasting of weather. The picture of the general circulation of the atmosphere thus developed is now being published in a contribution from the writer to the Yearbook of the Department of Agriculture for 1941.

Practice forecasts for five-day periods were carried out throughout this entire period. In August, 1940, the project was assumed to have reached such a state of development that an experimental five-day forecast-unit was organized to prepare, twice a week, overlapping five-day forecasts of temperature and precipitation-anomaly for telegraphic distribution to the regular Weather Bureau district forecast-centers, and after revisions and corrections in these forecast-centers, for distribution to the general public. All these forecasts are subjected to a rigid system of verification against observed mean data in order to gage the degree of success and to aid the forecasters in eliminating avoidable errors.

On June 1, 1941, the project was transferred to Washington, D. C., and set up as a regular service-project in the Central Office of the Weather Bureau. During the winter of 1940-41 the project was generously supported by financial contributions and professional assistance from the Army and Navy.

The basic ideas concerning the general circulation of the atmosphere underlying this forecast-project as well as the forecasting technique itself are still full of gaps and uncertainties, and hence research is more needed than ever, if real progress is to be made. The existence of a forecast-project of this type offers an unparalleled opportunity to organize cooperative research in meteorology along broad lines with a definite goal in mind and with a minimum of waste. The Weather Bureau is consequently supporting cooperative research-projects at several meteorological institutions, the results of which are expected to produce marked progress in our long-range forecasts.

(1) One of the basic discoveries made during the last few years from the study of five-day-mean pressure-charts concerns the intensity of the prevailing mean west-wind circulation in middle latitudes. A measure for the intensity of this five-day mean circulation at sea-level was found in the difference of the mean sea-level pressure at 35° north and at 55° north, taken around the Globe. This index has been found to vary between -5 mb (indicating prevailing east winds in middle latitudes) and +15 mb (indicating prevailing strong west winds). It was suggested by Commander Andersen (United States Navy) that these fluctuations might be due to intermittent influx of true equatorial air into the westerlies of middle latitudes. According to this hypothesis, a current of true equatorial air is occasionally injected into middle latitudes. There it interacts with the polar air along the polar front, and, because of the enormous amounts of latent heat available, the resulting intense vertical, meridional circulation over the polar front leads to a marked strengthening of the westerlies. This in turn leads to a build-up of the sub-tropical high-pressure belt and thus the equatorial air is shut off from access to higher latitudes. As the westerlies gradually are dissipated, the general circulation breaks down into smaller cells and there is renewed opportunity for equatorial air to flow northward. This hypothesis is now being tested statistically and synoptically in Washington, mainly with the aid of maps of the Northern Hemisphere for the International Polar Year to determine if there is time-lag relationship between the northward flow across latitude 20° north and the subsequent westward flow between 35° north and 55° north.

(2) Theoretical and synoptic investigations at the Massachusetts Institute of Technology have revealed that periods of strong west-wind circulation are characterized by intense and large cyclonic centers of action in the North Pacific and around Iceland while a weak west circulation normally is accompanied by a break-down of each of the Pacific and the Icelandic Lows into two weak separate low-pressure centers.

According to the theoretical results obtained at the Massachusetts Institute of Technology a strong west-wind circulation should result in the creation of long standing waves superimposed on the westerlies prevailing in the middle and upper portions of the troposphere in middle latitudes, whereas a weak west-wind circulation should lead to a marked break-down of the general circulation with standing waves of short wave-length. The wave-length of these standing waves determines the size of the centers of action observed on the sea-level charts. For each value of the west-wind circulation there is a definite stationary wave-length, shorter waves moving eastward and longer waves westward.

Until recently these ideas could not be tested quantitatively, since the sea-level charts give little or no information concerning the strength of the westerlies aloft. However, since January, 1941, three-km pressure-charts, covering most of the North Pacific, North America, and the North Atlantic, have been and are now being constructed which in many cases strikingly reveal an extremely regular wave-pattern superimposed on the upper westerlies. The data for these charts are obtained from direct observations (radiosondes) and through upward extrapolation of sea-level pressures and temperatures in oceanic regions where observations indicate approximately saturation adiabatic stratification. In Washington and at the University of Chicago, tests are now being made to determine empirically the relation between wave-speed, prevailing west-wind intensity, and wave-length on these maps.

(3) In studying the behavior of long waves in the westerlies, one encounters the difficulty that the west-wind belt normally increases in intensity upward throughout the entire troposphere. It is not a priori evident at which elevation the controlling west wind should be determined. This problem is now being studied theoretically at the University of Chicago. As a by-product, this investigation should shed considerable light on the distribution of vertical motion in long atmospheric waves.

(4) For forecasting purposes it is important to establish the relationship between the number, position, and character of the frontal systems associated with periods of strong and weak circulation, and to determine the conditions of weather and temperature characteristic of these different circulation-types. In so far as the Pacific is concerned, such an investigation is now being conducted in the Meteorological Department of the University of California at Los Angeles, the results of which should be of particular importance to short-range and long-range forecasting for the Pacific Coast States.

(5) An independent investigation of types of typical frontal patterns, and particularly of the transition from one type to another, has been conducted by Elliot at the California Institute of Technology under the direction of Professor J. Krick. The results of this investigation have not yet been published but apparently the principal types described by Elliot agree fairly well with the types classified by the group at the Massachusetts Institute of Technology on the basis of circulation-intensity. The Weather Bureau expects to support this investigation to make the results generally available within the near future.

(6) The forecasting procedure employed by Dr. Willett and his colleagues at the Massachusetts Institute of Technology is based on the construction of prognostic mean sea-level and three-km pressure-charts for the time-interval under consideration. Once these two pressure-distributions have been predicted the expected temperature-anomaly distribution is to some extent prescribed, since the pressure at three km and the pressure at sea-level together determine the mean temperature of the vertical air-column between these two levels. On the other hand, the relationship between the distribution of pressure and of the precipitation-anomaly is not nearly as simple. Work is now under way in Washington to determine this relationship and in this undertaking considerable use is made of the relationship between vorticity and horizontal convergence, and hence between vorticity and vertical motion.

(7) Particularly for military purposes, the forecasting of anomalies should be supplemented with studies of the day-by-day changes in conditions of weather during the forecast-interval. This problem is now being tackled in Washington in such a fashion that after the prognostic mean charts have been drawn a series of daily prognostic charts are drawn, compatible with the predicted mean state and evolving gradually from the latest available observed synoptic chart.

(8) A number of statistical investigations relating to the project are now under way and in addition it is planned to make use of punched cards for classification of five-day-mean data obtained since 1936.

(9) Returning finally to the basic circulation-model on which the entire project rests, the increasingly rich material of daily radiosonde observations from the stratosphere suggest that the stratospheric circulation may exert a stronger and more direct influence on developments in the troposphere than we have assumed until now. If this is so it may be necessary to revise our picture of the meridional circulation in atmosphere to include direct interaction between stratosphere and troposphere. We are attempting to solve this problem using atmospheric ozone to identify air of stratospheric origin. In this program the Weather Bureau, New York University, and the University of Chicago are cooperating.

To study the dynamics of the interaction between stratosphere and troposphere daily pressure-charts for heights of 10, 13, and 16 km are now analyzed both in Washington and at the University of Chicago.

University of Chicago,
Chicago, Illinois

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30–MAY 3, 1941

SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY

REPORTS AND PAPERS

WASHINGTON, D. C.
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UNITED STATES DEPARTMENTAL AUDITORIUM
9:00 A.M., APRIL 30, 1941

THE REDUCTION OF MAGNETIC OBSERVATIONS TO MEAN OF YEAR

E. H. Vestine

(Abstract)

Measurements of the Earth's main field are always affected by continuously varying electric currents flowing above and below the Earth's surface. During magnetic storms the Earth's field in low latitudes may be reduced by several per cent, and the gradual recovery of the field may continue for several days. The increase of field following the recovery-period of a storm may persist for a week or more, so that the field may attain values considerably in excess of the annual mean value. This effect is often also found in the case of small and moderate disturbances of the Earth's field, and has caused serious difficulty in the task of estimating the changes in the main field appearing from year to year.

Using extensive data of the Polar Year, 1932-33, it was found that monthly mean departures from annual mean values at magnetic observatories vary in a systematic way with position on the Earth. These systematic changes with position depend in a marked way upon geomagnetic latitude. The geomagnetic north component of these departures is small near the geomagnetic poles and is greatest near the auroral zones. Just outside the auroral zone this component diminishes rapidly with decreasing geomagnetic latitude and attains a secondary maximum near the equator. The changes in the geomagnetic east component are comparatively very small in all latitudes. The vertical component is large inside the auroral zone, small in middle and low latitudes, and very small or zero at the equator. These departures show a field clearly symmetrical about the geomagnetic axis and equator upon which is superposed a similar field depending locally in intensity on season of year.

The daily mean departures from monthly mean values give rise to a world-wide distribution of field of a general type similar to that found in the case of monthly departures from the annual mean. The marked dependence of these departures on geomagnetic latitude permits a convenient means of correcting field-observations (during magnetic surveys) to mean of year, by interpolating the departures on the day of observation noted at a few magnetic observatories to the north and south of the stations. In the case of a number of days on which field-observations were made by the Department of Terrestrial Magnetism it was found that the range in the daily mean departures from the annual mean value was as great as 45γ. The investigation further shows that if field-observations extend continuously over an entire day it is then in general possible to reduce the observed value to mean of year with a considerable degree of precision. The study is being continued to include methods of reduction of mean hourly values to mean of day, and hence to mean of year, although there appears little prospect of developing a highly successful method in this instance.

[The complete paper is to be published in the Journal of Terrestrial Magnetism and Atmospheric Electricity.]

Department of Terrestrial Magnetism,
Carnegie Institution of Washington,
Washington, D. C.

IMPROVEMENTS AND MODIFICATIONS TO A LA COUR MAGNETOGRAPH

J. H. Nelson and A. K. Ludy

Three la-Cour variometers, formerly a part of the Polar-Year equipment used at College, Alaska, were modified for installation as the regular sensitive magnetograph to be installed in the new variation-observatory constructed during 1939 at Tucson, Arizona. Several changes were made in each variometer, both before they were set up and during the preliminary trial-period in the Test Laboratory at the Cheltenham Observatory. After all changes had been made, the instruments were given a final test-period of several weeks at Cheltenham to insure their satisfactory operation.

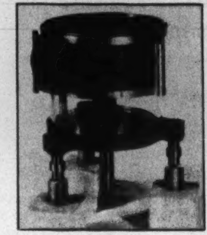

Fig. 1

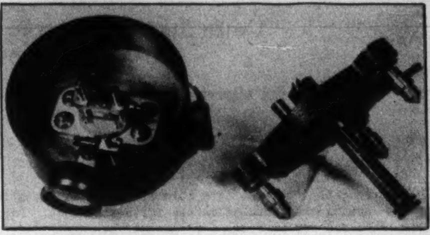

Fig. 2

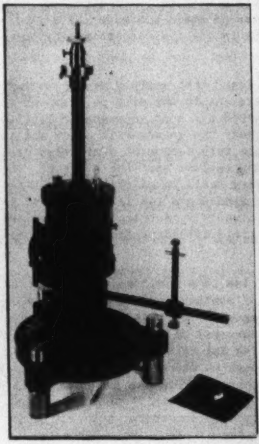

Fig. 3

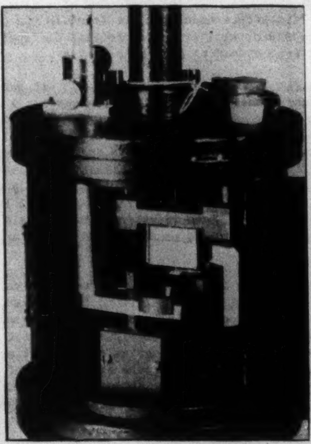

Fig. 4

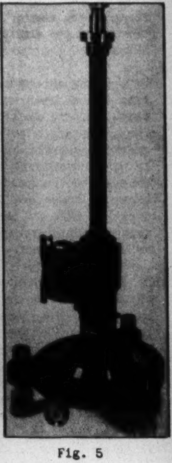

Fig. 5

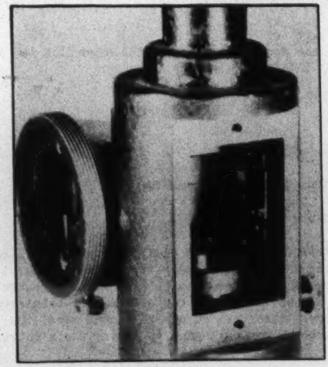

Fig. 6

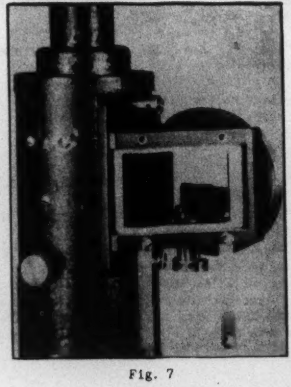

Fig. 7

Z-variometer--In the original la Cour variometer, temperature-compensation was achieved by an optical method, whereby the reflecting prism was mounted on a bimetallic strip which displaced the prism, and hence the light-spot, by an amount just equal and opposite to the displacement of the spot caused by the change in the position of the recording magnet with temperature. This method was quite suitable for the conditions of operation for which la Cour designed his variometers, namely, operation in polar regions where relatively large scale-values were used and large degrees of magnetic disturbance were encountered. In the present instance, however, a scale-value of the order of three to four gammas per millimeter was desirable, and the actual changes in the magnetic elements were those encountered at low-latitude stations. Under these circumstances, it was not desirable to permit the Z-magnet to be displaced from the normal level position by temperature-effects, as such displacements would introduce second-order effects in scale-value as a result of possible asymmetrical knife-edge sections, as well as introducing corrections for variations in horizontal intensity. To overcome these objections, magnetic compensation was substituted. The effective length of the bimetallic strip was reduced to zero and a holder was made to support an Alnico temperature-compensating magnet vertically under the Z recording magnet (see Figs. 1 and 2). A metric scale on the holder permits relative settings of the compensator to within about 0.1 mm, while the distance between compensator and knife-edges as shown on the scale engraved on the compensator-holder is known to ±1/4 mm. The compensating magnet is seven mm in diameter and 35 mm long. It was first magnetized to saturation and then reduced in moment by subjecting it to a 60-cycle alternating magnetic field until it measured 197.0 cgs units.

In reducing the effective length of the bimetallic strip to zero, the reflecting prism was brought nearly opposite the center of the variometer-lens, resulting in complete shielding of the base-line mirror. Therefore, a new base-line mirror holder was constructed and mounted as shown in Figure 2. It is completely adjustable in azimuth and elevation; the mirror may be rotated about an axis normal to its plane for orientation. The mirror is silvered on its back surface; it is 7.5 mm in diameter and 1/2 mm thick.

The scale-value of the Z-variometer was adjusted to approximately 3.7 gammas per mm at Cheltenham by honing the Z-magnet near the ends. (A la Cour Z-magnet should never be honed near its center as this causes the mirror-surface to warp.)

H-variometer--The la Cour H-variometer, as originally designed, also used the optical method of compensation which has already been described in the case of the Z-variometer. As in the latter instrument, this method was entirely suitable for polar operation but since it permitted the H-magnet to move out of the prime vertical with temperature-changes it was not deemed satisfactory for operation at Tucson, as such misorientation would introduce corrections in the indicated H-variations due to changes in declination. Therefore, the optical compensation was eliminated by reducing the effective length of the bimetallic strip to zero and a holder was made to support a 36 per cent cobalt-steel compensating magnet, five mm in diameter and 25 mm long, plated with chromium (see Fig. 3). A brass pointer was provided so that it could be put in the magnet-holder for orientation, adjustment, and measurement of the position of the holder before actual installation of the magnet. Two windows provided with screw-on covers were cut in the sides of the variometer to permit the end of the brass pointer to be pushed to the center of the variometer. The compensating magnet was first magnetized to saturation and then reduced in moment until it measured 88.6 cgs units. Temperature-effects on the upper prism of the variometer were eliminated by bolting the prism-holder directly to the horizontal supporting bar. The bimetallic strip was reduced to zero but was left in place for possible future use.

A mirror having three plane faces was mounted on the mirror-frame attached to the recording magnet. The angle between successive faces was chosen so that a reserve-spot was provided on either side of the regular recording spot at distances from the latter of about 19 cm, or about one cm less than the width of the magnetogram, when the variometer was placed at the proper operating distance from the recorder. The mirror is aluminized on the front side and the quality of all faces is excellent.

The H recording magnet is two mm in diameter and ten mm long, 36 per cent cobalt-steel chromium plated. After saturation its moment was reduced to approximately 7.7 cgs units. This gives a scale-value of about three gammas per mm when used with the particular quartz fiber selected.

Damping of the magnet-system was found to be necessary. This was accomplished by supporting an adjustable copper damping-box, open at the top, on a rod mounted through the top of the variometer housing, as shown in Figure 4. The inside diameter of the box is 14 mm; the outside diameter is 18 mm; the thickness of the bottom is three mm and the depth inside the box is two mm.

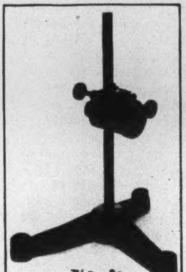

Fig. 8a

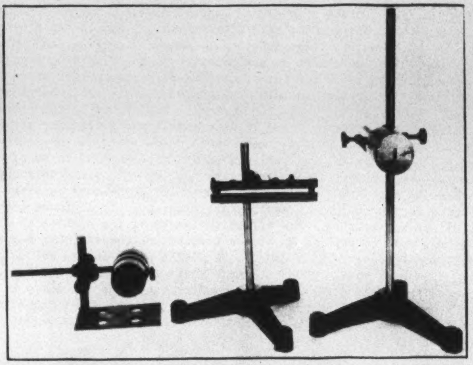

Fig. 9a Fig. 9b Fig. 9c

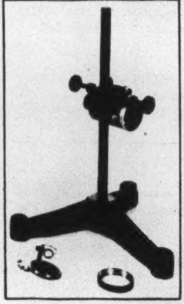

Fig. 8b

D-variometer--Current practice at all the observatories of the United States Coast and Geodetic Survey has been to operate D-variometers at scale-values of approximately one minute of arc per mm, as determined by the distance of the D-variometer from the recorder-drum, with two small corrections, one depending on the type and thickness of the variometer-lens and the other, the torsion-constant of the variometer-filament.

At low- or intermediate-latitude stations, such as Tucson, a D scale-value of one minute of arc per mm corresponds to a gamma scale-value of the order of eight to nine gammas per mm. When compared with the H and Z scale-values normally used of less than half this amount,

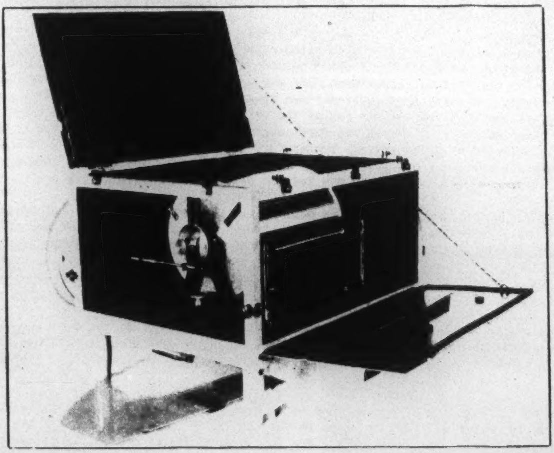

Fig. 10

D-scalings, both hourly and base-line ordinates and three-hour-range indices, cannot be determined with the same ease or accuracy as similar H- and Z-scalings. To remedy this difficulty, the D-variometer for Tucson was modified to give a scale-value of about 0!5 mm when used at the regular distance from the recorder. This was done by using a second reflection on the suspended mirror.

The magnet of the D-variometer is two mm in diameter and ten mm long; it is made of 36 per cent cobalt-steel, chromium plated. It was first saturated, then demagnetized until its moment was about 8.7 cgs units.

The D-mirror is seven by 22 by two mm, aluminized on the front surface. The stationary mirror, for the double reflection, is a three-faced mirror similar to the H-mirror described above except for slightly different angles between the mirror-faces. It is mounted on a three-point la Cour type holder inside the variometer-house facing the recorder (see Fig. 6). A new base-line mirror and holder were made. It was found that when the stem supporting the recording magnet was hung in front of the regular base-line mirror, the quality of the base-line spot suffered. The new base-line mirror-holder is mounted immediately behind the lens of the variometer. The holder consists of a horizontal triangular bronze plate on the front edge of which the mirror is mounted. The plate is fastened to the variometer by a single screw though its center. It is adjusted in azimuth from outside the housing by turning an eccentric screw operating in a slot in the plate. The forward edge of the plate on which the mirror is mounted is adjustable in elevation by a screw which bends the edge of the plate slightly. The original prism used on the side of the la Cour D-variometer was replaced by a first-surface-aluminized glass plane-mirror made from an old sextant-mirror, size 25 by 40 by 4 mm.

Damping of the magnet-system was found desirable and this was accomplished by supporting a copper damping-box, open at the top, on a vertical rod extending up through the floor of the magnet-chamber. The damping-box is adjustable in height only. Its dimensions are the same as the damping-box used in the H-variometer, described above.

Thermograph--Since the bimetallic strips in both the H- and Z-variometers were rendered inoperable by reducing their lengths to zero, it was necessary to provide another element in the magnetograph for recording temperature on the grams. One end of a bimetallic strip (gold and platinum) about 2.5 cm long, bent in a circular form, was mounted in a suitable housing. On the other end of the strip a first-surface-aluminized mirror was mounted and a suitable lens was placed in front of the mirror so that the thermograph could be installed between the D- and Z-variometers. The scale-value of the temperature-curve is approximately 0°4/mm (see Fig. 8).

Time-flashing system--The equipment for providing the time-lines across the magnetogram consists of a lamp-holder with a short piece of cylindrical lens mounted on it, together with a plane mirror with an adjustable horizontal-slit diaphragm mounted on a stand. The lamp-holder is placed beside the recording box and the mirror is located on the pier beside the H-variometer in such a way that the light from the time-flash lamp is reflected directly on the cylindrical lens of the recorder (see Fig. 9).

Recorder--The recorder, illustrated in Figure 10, was built from parts obtained from other equipment, with the addition of a new clock-movement and suitable gears and other driving mechanism. The box is part of an old Toepfer instrument; the drum is a portable tide-gage-type cast aluminum drum mounted on a bronze shaft. The new clockwork, a Seth Thomas No. 10A movement, is mounted on the outside back of the recording box and has been altered only by reversing the minute-hand shaft so that it projects from the back of the clockwork instead of the front, the frame being rebushed where necessary. The original shaft is used. Through a universal joint, the shaft is made to turn a quadruple-thread worm mounted on the drum-rack; the worm meshes with and drives a 100-tooth, 48-pitch quadruple-thread worm-gear mounted on the drum-shaft. The clockwork therefore runs at its normal rate (without special escapement-wheel, balance-wheel, hairspring, or odd gears) and drives the drum at the rate of one revolution in 25 hours which gives a paper speed of 20 mm per hour. An adjustable friction-clutch between the worm-gear and the drum-shaft allows the drum to be turned by hand when changing records without engaging or disengaging a clutch and without danger of spoiling clock-gears or bearings. The drum-shaft bearings are open at the top, permitting the drum and shaft to be lifted out of the recorder-box quite easily.

Diaphragms--Each of the three variometers is equipped with an adjustable horizontal-slit diaphragm mounted outside the lens as shown in Figures 1, 3, and 5. By means of these diaphragms the intensity of the light-spot at the drum may be adjusted so that the spots from all the mirrors are of equal brilliancy.

Conclusions--During the final test-period at Cheltenham following the completion of all alterations to the magnetograph, excellent records were obtained. The quality of the light-spots was considerably better than the average now being realized, and it is anticipated that upon its final installation at Tucson, the new magnetograph will constitute a marked improvement over the present equipment at the Observatory.

U. S. Coast and Geodetic Survey,
Washington, D. C.

A COMPUTATION OF THE AVERAGE DEPTH TO THE BOTTOM OF THE EARTH'S MAGNETIC CRUST, BASED ON A STATISTICAL STUDY OF LOCAL MAGNETIC ANOMALIES

Victor Vacquier and James Affleck

It is recognized that the Earth's crust is composed of a sedimentary layer of from zero to perhaps ten miles in thickness, a magnetic granitic layer, and an underlying layer which is either non-magnetic or is uniformly magnetic. The sedimentary layer may in general be considered non-magnetic, since only relatively weak magnetic anomalies originate from this source. The lower layer may correspond to the basaltic layer and, from considerations of temperature and plasticity, this rock may be completely non-magnetic or, on the other hand, since no reliable information is available, it is equally possible that it is homogeneously magnetic. The Curie point for basaltic material is about 475° C, according to Chevallier [see 1 of "References" at end of paper], and this temperature should be attained, according to Benfield [2], at an average depth of from 11.4 to 15.7 miles below the Earth's surface. On the other hand, gravity-anomalies, apparently due to density-contrasts at much greater depth, are not uncommon.

The intermediate layer is granitic and magnetic. The large local magnetic anomalies on the Earth's surface are caused by changes of the magnetic character of the rocks in this zone. Figure 1 is a generalized sketch of the disposition of the three layers. In the middle layer, three zones of higher magnetic polarization are shown. The vertical magnetic intensity on the Earth's surface is proportional to the solid angle subtended by the upper surface of the highly magnetized zone, minus the solid angle subtended by the lower surface. This is based upon the assumption that the rocks are polarized vertically and that there are vertical contacts between the zones of high and low polarization. Obviously, therefore, the shape and relief of the magnetic anomaly at the Earth's surface will depend upon the depth to the top of the granitic zone, the depth to the bottom of that zone, the difference between the high and low polarizations $(I_2 - I_1)$, and, of course, upon the shape of the cross-section of the vertical column of polarization I_2. Since there is considerable variation in the depth to the top, it should be possible to calculate an average value for the depth to the bottom of the granitic zone, or at least the inhomogeneous magnetic zone, since the base of the inhomogeneities is all that we can hope to determine. These calculations can be made if it is found possible to determine the shape of the cross-section and the depth to the top. The difference $(I_2 - I_1)$ is not constant for the anomalous conditions, so that this unknown is also present. If enough anomalies can be studied it is probable that the average polarization-contrast $(I_2 - I_1)$ for shallow sedimentary areas will be reasonably close to the average polarization-contrast in areas of greater sedimentation. By a statistical study of a large number of anomalies, then, it should be possible to select a value for the average depth to the bottom of the magnetic inhomogeneities.

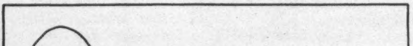
VERTICAL MAGNETIC INTENSITY
EARTH-SURFACE
NON-MAGNETIC SEDIMENTARY LAYER
I_1
I_1
I_1 MAGNETIC GRANITIC LAYER
I_2
I_1
I_2
I_1
ZONE OF NON-MAGNETIC OR UNIFORMLY MAGNETIC MATERIAL

Fig. 1

In Figure 1, it will be observed that the angle subtended by the bottom on the narrow anomaly at the extreme right is very small, so that the bottom-effect is negligible. The character of the magnetic anomaly is therefore practically independent of the bottom-effect. Calculations of the depth to the top and of the shape-factors can be estimated on these narrow anomalies. By the same reasoning, only the wide anomalies such

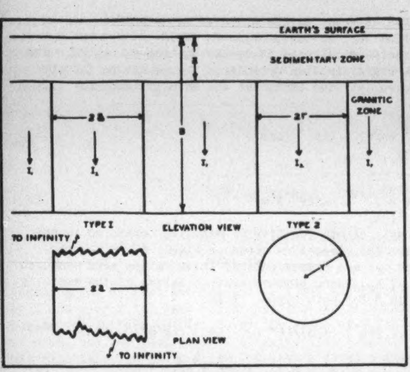

Fig. 2

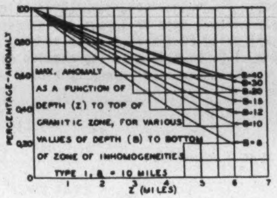

Fig. 3

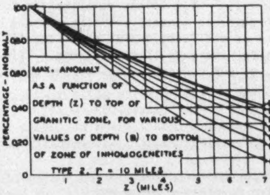

Fig. 4

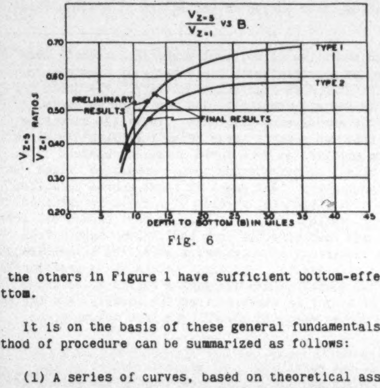

Fig. 6

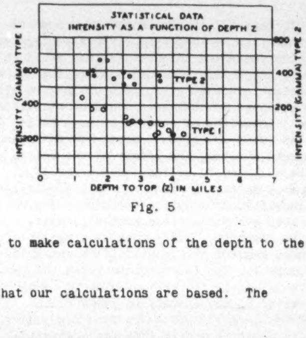

Fig. 5

as the others in Figure 1 have sufficient bottom-effect to make calculations of the depth to the bottom.

It is on the basis of these general fundamentals that our calculations are based. The method of procedure can be summarized as follows:

(1) A series of curves, based on theoretical assumptions on idealized polarization-contrasts, was drawn. These curves show the variation of the maximum anomalous vertical intensity with change in depth to the top of the magnetic igneous layer, with the depth to the bottom of this layer as a parameter. Figure 2 shows the assumed distributions of polarization, and Figures 3 and 4 give samples of the curves.

(2) Magnetic anomalies, 126 in number, were selected from contour-maps of vertical magnetic intensity over large portions of the United States and other countries. The anomalies selected fell into two classes of types. Depths to the top and shape-factors were determined, and for each type statistical data showing intensity as a function of depth were plotted. Figure 5 shows these data.

(3) By a curve-matching scheme, the best fits between the theoretical curves and the statistical curves are found for each type of anomaly, thus obtaining two independent solutions of the depth to the bottom of the inhomogeneous magnetic layer. Figure 6 demonstrates the curve-matching scheme.

In part (1) of the method of procedure, certain simple geometric figures must be chosen. These are demonstrated in Figure 2. From experience we have found that in the majority of cases vertical polarization with vertical contacts can be assumed. Two types of anomaly are common, namely, the elongated elliptical type and the circular type. The elongated elliptical type, which we call Type 1, is typified by those anomalies where the contours are generally elliptical in shape with the major axis perhaps three times as great as the minor axis. A profile across the center of this type of anomaly is almost identical to the profile in Figure 2 over the dyke-like polarization-contrast of infinite length perpendicular to the cross-section direction. The circular or Type 2 anomaly is represented as a right circular cylinder. The equations for the maximum vertical magnetic intensity (which occurs over the center of the anomaly) are, for Type 1 anomalies

$$V_{max} = 4\Delta I\ [\tan^{-1}(a/z) - \tan^{-1}(a/B)] \qquad (1)$$

and for Type 2 anomalies

$$V_{max} = 2\pi\Delta I\ [B/(r^2 + B^2)^{1/2} - z/(r^2 + z^2)^{1/2}] \qquad (2)$$

where $\Delta I = (I_2 - I_1)$ is the polarization-contrast, either positive or negative, measured in cgs units of magnetic moment, and a, z, B, and r are the dimensions shown on Figure 2. Since the arguments of the functions of equations (1) and (2) are dimensionless, these values were measured in miles for the sake of convenience. Values of V_{max} were plotted against values of the depth to the top, z, for various values of the base depth B for both types. Then

$$(V_{max}/V_{max(z=0)}) = [\tan^{-1}(a/z) - \tan^{-1}(a/B]/[(\pi/2) - \tan^{-1}(a/B)] \qquad (3)$$

and

$$(V_{max}/V_{max(z=0)}) = [B/(r^2 + B^2)^{1/2} - z/(r^2 + z^2)^{1/2}][(r^2 + B^2)^{1/2}/B] \qquad (4)$$

give the percentage-change in the anomaly with a change in z for various values of B. Figures 3 and 4 give samples of these curves. By calculating these curves as percentage of maximum value, ΔI is eliminated.

In part (2) of the method of procedure, 126 anomalies of vertical magnetic intensity were selected from contour-maps. These contour-maps had a sufficiently dense array of stations so that the shape and intensity-values could be estimated with reasonable accuracy. The areas covered by these maps included most of the States in the mid-Continent, and some foreign areas. Altogether somewhat over 1,000,000 square miles of survey were available. These 126 anomalies were selected so that they could be classified into two groups, these being the types described above. Anomalies of abnormally high relief were omitted, as were those anomalies where a or r was less than 6.0 miles. Depth-estimates were made from neighboring narrow anomalies, since, as mentioned earlier, the effect of the bottom is negligible. The shape of these narrow anomalies can be utilized to estimate the value of z. In some instances, a value of z could be obtained from well-depths or other reliable geological information. Values of a and r were picked off from the anomalies by graphical methods. The relief was read directly from the contour-maps. This last step was perhaps the most difficult, since the effect of neighboring anomalies is not always easy to identify. Table 1 shows a sample of our data-sheets. The first column shows arbitrarily assigned numbers for identification-purposes. The second column designates the type, as shown in Figure 1. The third column gives the value of a or r as measured from the anomaly, and the fourth column is the estimated depth to the top of the magnetic layer. The last column gives the relief of the anomaly in gammas.

In order to derive from the statistical data the relationship of magnetic relief to the depths z and B, the anomalies were arranged in groups and sub-groups according to the values of z and a or r. Averages of V, z, and a or r, calculated for each sub-group, formed the basisof later calculations.

Table 1--Portion of data-sheet

Anomaly No.	Anomaly No.	a or r	z	V in gammas
1	2	10.0	3.5	-220
2	1	7.6	2.5	+200
3	1	7.0	3.0	+150
4	2	6.2	3.7	+470
5	2	10.0	1.5	+1200
6	1	7.0	2.5	+900
7	2	12.0	2.0	-450
33	1	13.0	4.8	-200

All anomalies of Type 1 where "a" lies between 6.0 and 7.0 were selected, then those for which "a" is between 7.1 and 8.0 made a second group, and so on. Each group was then subdivided into sub-groups which consisted of those anomalies whose values of z lay between 0 and 1.5, 1.0 and 2.0, 1.5 and 2.5, etc. Anomalies of Type 2 were similarly divided and subdivided. Arithmetic averages of a or r, z, and V for each sub-group were then taken. Each sub-group therefore contributes one, and only one point on a curve, which curve, if the value of ΔI were known, should be similar in character to some one curve of the type shown in Figures 3 and 4, which are calculated for idealized distributions of polarization. To afford a method of comparison, it is necessary to adjust the observed and calculated values so that the effect of the various values of a and r can be eliminated. Since the average values for a and r for all anomalies were in the neighborhood of 10.0, the average values of V and z calculated for the sub-groups can be corrected or adjusted in such a manner that the effect of values of a and r other than 10.0 would be eliminated. Equations (5) to (7) follow.

$$V_{max(a=10)} = 4\Delta I\ [\tan^{-1}(10/z) - \tan^{-1}(10/B)] \tag{5}$$

and

$$f_1 = \frac{V_{max(a=10)}}{V_{max(a=a)}} = \frac{\tan^{-1}(10/z) - \tan^{-1}(10/B)}{\tan^{-1}(a/z) - \tan^{-1}(a/B)} \tag{6}$$

and similarly

$$f_2 = \frac{V_{max(r=10)}}{V_{max(r=r)}} = \frac{B/(100 + B^2)^{1/2} - z/(100 + z^2)^{1/2}}{B/(r^2 + B^2)^{1/2} - z/(r^2 + z^2)^{1/2}} \tag{7}$$

Assuming for a first attempt that B = 20, and substituting in equations (6) and (7) the values of z and a or r for each sub-group, the values obtained are correction-factors. The appropriate correction-factors multiplied by the value of V for the corresponding sub-groups give two sets of data, one for each type of anomaly. The supposition is, therefore, that if the bottom of the magnetic layer is at 20 miles, we have a large number of anomalies where a and r are ten miles. We can therefore plot the average value of V for each sub-group against the corresponding value of z for that sub-group, thus getting two sets of points, one for each type of anomaly. It is still not possible to plot a curve, since each individual point has involved as a multiplicative factor a particular value of ΔI. Figure 5 shows the group of points for the two types of anomaly. It is obvious from Figure 5 that it would be necessary to know ΔI for each point, to reduce the values to a common basis for plotting.

However, by means of a weighted least-square adjustment, the effect of the various values of ΔI can be minimized.

A straight-line equation

$$V = (pz + q) \tag{8}$$

was decided upon since the theoretical curves of Figures 3 and 4 are fairly close to a straight line in the region in which we are interested, namely, from z = 1.5 to z = 4.5. If w is the number of anomalies which were averaged to give the value for any particular point in Figure 5 then it is easily shown that

$$q = (\Sigma wV\ \Sigma wz^2 - \Sigma wz\ \Sigma wzV)/[\Sigma w\ \Sigma wz^2 - (\Sigma wz)^2] \tag{9}$$

and

$$p = (\Sigma w\ \Sigma wzV - \Sigma wz\ \Sigma wV)/[\Sigma w\ \Sigma wz^2 - (\Sigma wz)^2] \tag{10}$$

The straight lines for the two types of anomalies obtained from these equations are shown on Figure 7.

A similar least-square adjustment was made on each curve of Figures 3 and 4, in the zone from z = 1.5 to z = 4.5, thus eliminating any error which might have been introduced by the use of the straight-line adjustment on the statistical data.

The curves in Figure 7 are still in intensity-units, and thus depend upon some average value of ΔI. It was therefore necessary to devise a scheme for eliminating ΔI. The straight-line adjustment through the theoretical curves can be represented by

$$V = K\ (z + C) \tag{11}$$

and the line through the statistical data by

$$V = m\Delta I\ (z + C) \tag{12}$$

where K, C, and m are the unknown constants. Then from both (11) and (12)

$$(V_{z=5}/V_{z=1}) = (5 + C)/(1 + C) \tag{13}$$

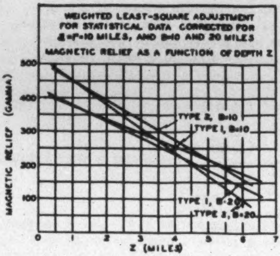

Fig. 7

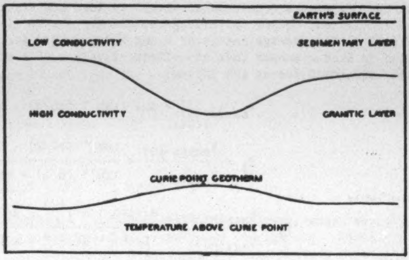

Fig. 8

and K, m, and ΔI have been eliminated. The ratio $(V_{z=5}/V_{z=1})$ was therefore calculated graphically from the straight-line adjustments through the curves of Figures 3 and 4, and a plot of $(V_{z=5}/V_{z=1})$ against B was drawn. This is shown in Figure 6. From the straight-line adjustments through the statistical data (Fig. 7), the corresponding ratios were calculated. By locating these statistical ratios on the curves of Figure 6, we therefore can read off the value of the depth to bottom (B). For Type 1 anomalies we get 12.2 miles and for Type 2 we get 9.0 miles. Obviously, therefore, our assumption of B = 20 for corrections for variation of a and r is not close enough. A new estimate of B = 10 gives new straight-line adjustments and new values of B of 13.0 miles and 12.3 miles, as shown on Figures 6 and 7.

The effect of B in the corrections for variation of a and r is therefore of a second order. Obviously, by repeated trial and error, an exact value of B could be selected, but the change from B = 13.0 and B = 12.3 for the two types would be insignificant. A separate computation involving an independent selection of the quantities tabulated from the original magnetic maps was made by the other author in order to attempt to eliminate any personal effects, and this gave values of B = 14.0 and B = 12.3, respectively. From all of these we have selected the value of B = 12.5 as the best probable value.

The assumption was made that the anomalies are due to zones of polarization-contrasts, and that these zones have vertical boundaries. If one considers that the positive magnetic anomalies may be caused by intrusions of basaltic material into the granitic zone, then perhaps in some instances the boundaries are sloping, and the zones may have the form of truncated cones. The so-called negative anomalies will therefore obviously have reverse slopes. Since nearly equal numbers of positive and negative anomalies were used, the overall results will cancel the effects of such sloping contacts, if they exist.

This value calculated for B falls in the range of values given by Benfield [2] and, from this point of view and others, seems to be an entirely reasonable depth. From the nature of the solution, we can come to the conclusion that the bottom of the layer of magnetic inhomogeneities is at an average depth of between 11 and 15 miles from the Earth's surface. Since gravity-data often indicate density-contrasts at much greater depth, it is reasonable to interpret the depth we obtained for the bottom of the zone of magnetic inhomogeneities in the Earth's crust as coinciding with the depth of the Curie-point geotherm. If relative conductivities of sedimentary and igneous rocks be considered, then it is reasonable to deduce that the bottom of the magnetic layer should be closer to the surface in areas of deep sedimentary basins than in areas where the igneous material is close to the surface. Figure 8 is illustrative of this. This would indicate that the values of $(V_{z=5}/V_{z=1})$ taken from the statistical data are too small by a few per cent. The value for the depth B might therefore be increased somewhat. It is encouraging to find that from the two entirely separate points of view of heat flow and magnetic effects the final conclusions are almost identical.

We are indebted to the officials of the Gulf Research and Development Company for permission to publish this paper.

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A COMPARISON OF TWO SETS OF TRANSCONTINENTAL MAGNETIC DATA

George P. Woollard

(Abstract)

The writer working under a grant from the Geological Society of America and using Askania Schmidt type vertical-component magnetometers established a series of magnetic observations across the Continent in the summer of 1940. These observations were part of a general program of magnetic and gravitational investigations undertaken to study the degree of geologic correlation that existed between these data and known regional geologic features. The traverse was run from Sea Bright, New Jersey, on the Atlantic Coast, to Morro Bay, California, on the Pacific Coast, and crossed such geologic features as the Appalachian Mountains, the Cincinnati Arch, the Illinois Basin, the Ozark Uplift, the Rocky Mountains, the San Joaquin Valley, and the Pacific Coast Ranges.

For control, a line of base-stations about 35 miles apart was first established across the country and these bases were reoccupied in making the final traverse on which there was a spacing of about five miles between stations. The procedure used in establishing the base-stations was to make a series of closed loops so that each station was tied by repeat-observations to both the station in front of and behind it, and this also permitted a check to be obtained upon the diurnal variation in the Earth's magnetic field as well as any base-station correction. Although the diurnal variation was checked by observations with the second instrument in the first part of the survey, this was not possible for the bulk of the survey as one instrument was badly damaged in an automobile accident at St. Louis and lost to the survey until the detail return-traverse was started. On the return-traverse the diurnal variation was observed by taking continuous observations with one instrument stationary during the period of the day's run with the other instrument. Since no repeat-observations were made with the moving instrument, the difference between the magnetic interval observed between base-stations on the two traverses after making the diurnal correction was assumed to represent the base-station correction for that instrument. These differences were in part due to lack of precision in reoccupying the exact sites of the original stations, and so any base-station correction was taken as the mean of this departure-curve rather than the actual difference at each station.

A comparison of the magnetic intervals between bases on the two traverses shows that throughout the same magnetic picture is indicated with most changes being of the order of magnitude of 300 to 400 gammas in relatively undisturbed portions of the country and around 1,000 gammas in those areas where igneous rocks are at, or close to, the surface. The average check over the entire traverse for these base-station intervals was around 50 gammas, and the accumulative difference reached a high value of about 400 gammas over part of the survey with a final closure of the entire traverse of 240 gammas. As a rough check on the total-intensity difference measured from coast to coast, the vertical-intensity values for the base-stations were determined from the United States Coast and Geodetic Survey magnetic map for 1935 and corrected to 1940. This profile and the base-station profile showed excellent agreement throughout with a closure of 81 gammas on a total change of 9,710 gammas.

[The complete results of these investigations will be published in the Bulletin of the Geological Society of America.]

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GEOMAGNETISM AND THE AURORA

C. W. Gartlein

(Abstract)

In 1741, Celsius and Hiorter pointed out the simultaneous occurrence of an aurora and a magnetic storm. About the same time some aspects of the aurora were related to the usual geomagnetic field. Now we know that auroras occur most frequently in regions about 23° from the geomagnetic poles. Normal auroral arcs are nearly at right-angles to the geomagnetic meridian. The rays of the aurora are closely parallel to the lines of magnetic force.

The geomagnetic field is subject to storms which occur most frequently near the equinoxes.

Auroras are likewise most frequent then in lower latitudes (45° to 60° geomagnetic). There is also an approximate 11-year cycle of magnetic storms and of auroras, whose peak comes after the peak of the sunspot-cycle. Magnetic storms are accompanied by auroral displays in the lower latitudes, extending farther from the poles during the more intense storms.

The above relations were shown from data taken by the National Geographic Society-Cornell University Study of Aurora, 1938-41, and from older observations in New York State. In particular, the development of the aurora of March 30, 1941, was shown, as well as the location of coronas, inclination of rays, and direction of normal and abnormal arcs.

A correlation has been obtained between the magnetic K-figure and estimated auroral character-figures for 226 intervals. The coefficient of correlation is 0.63.

Intensities of the green auroral line obtained in three-hour exposures with a patrol spectrograph show some correlation with the magnetic K-figures in the range 0 to 5.

[This paper is to be published in the Proceedings of the American Philosophical Society.]

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IONOSPHERE-OBSERVATIONS AT THE 1940 eclipse in Brazil

T. R. Gilliland

(Abstract)

Results obtained from ionosphere-measurements made during the solar eclipse of October 1, 1940, in Brazil are described. The Expedition was sponsored jointly by the National Bureau of Standards and the National Geographic Society. The observations were made at Patos in Parahyba State, about 240 miles inland from the coastal city of Pernambuco.

The equipment used was specially built for operation in the field and was self-contained including storage-batteries and a gasoline-engine-driven generator as a source of power. The transmitter-receiver unit was arranged to sweep through a frequency-range from 790 to 14,000 kilocycles in one minute.

During the eclipse, which had a period of totality of 282 seconds at the ground, the ionization-density of the E- and F_1-layers decreased to about 25 per cent of normal. The minimum density corresponds to a recombination-coefficient of about 2×10^{-8} for the E-layer and about 10^{-8} for the F_1-layer. The rate of decrease, however, and the fact that the time of minimum density occurred at the middle of totality, indicate practically infinite recombination-coefficients. An apparent anomalous effect was observed, in that the ionization began to increase before third contact.

In the case of the F_2-layer, information was not complete, but the minimum of ionization-density approached approximately half of normal, and apparently reached a minimum about an hour after totality. Up to the end of totality, the decrease in ionization corresponded to a recombination-coefficient of about 10^{-10}, but the density observed some time after totality was much less than would have been expected for this coefficient.

A definite decrease in ionization-density was observed at the same time that the moon obscured a large sunspot. This may be significant as indicating the source of some ionizing radiation.

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DIURNAL VARIATION IN ELECTRICAL RESISTANCE OF THE VERTICAL COLUMN OF THE ATMOSPHERE AT WATHEROO, WESTERN AUSTRALIA

G. R. Wait and O. W. Torreson

(Abstract)

The total resistance encountered by the current of electricity passing between the Earth and upper conducting layer does not remain constant through the day, but varies in a systematic manner. The resistance is greatest during the early morning hours and is least about 10^h local time. The seasons at Watheroo can be divided into wet and dry. The potential-gradient has a diurnal variation of vastly different type during the two seasons. The variation during the dry season agrees well with that found over the oceans while during the wet season there is complete lack of agreement. The total resistance, on the other hand, has essentially the same type of variation during the dry and wet seasons. The different types of diurnal variation in potential-gradient in the two seasons may be attributed, therefore, to the difference in the conductivity near the ground for the two seasons.

The diurnal variation in total resistance at Watheroo has been compared with that found for Huancayo and Tucson. When each is plotted on its own local time, a decided similarity exists in the curves for the three places. The similarity is still further enhanced by comparing the curves according to season of the year rather than by the month. These results suggest that some factor, which produces the variation, acts over land but not over the ocean, and that it varies through the day according to local time. Additional work will be required to definitely determine what this factor is.

The total resistance of the air at a given station and the resistance near the ground at that station nave different types of diurnal variation. This suggests that the air over the station may be regarded as made up of at least two layers which have different types of resistance-characteristics, namely, a lower layer near the ground, in which the conductivity-measurements are made, and a layer above this for which one may only deduce the resistance. It is of interest to obtain an estimate of the height to which this lower layer extends and to deduce the diurnal variation in resistance for the upper layer. An estimate has been obtained of this height for the period May to September, 1928, when there were simultaneous measurements of potential-gradient and conductivity over the ocean aboard the Carnegie and for both Watheroo and Huancayo. This height at Huancayo is about 1.5 km, the approximate height of the lower part of the Cumulus clouds, while at Watheroo the height is about 1.0 km. Assuming these heights to be correct, it was possible to deduce the diurnal variation in resistance for the upper layer at each station. The minimum in resistance of the upper layer occurs at about 10^h local time at both stations, in agreement with that found for the total resistance. The diurnal variation in resistance of the lower layer, therefore, plays but a small part in determining the character of diurnal variation in resistance encountered by the air-earth current between the Earth and the upper conducting layer.

[The complete paper is to be published in the Journal of Terrestrial Magnetism and Electricity.]

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THE PRODUCTION OF NEUTRONS BY THE COSMIC RADIATION

S. A. Korff

(Abstract)

Present estimates of the neutron-intensity associated with the cosmic radiation are obtained from experiments using several techniques, namely, proportional counters, ionization-chambers, induced radioactivity, and photographic plates [see 1 of "References" at end of paper]. The various techniques can be shown to give results which are in order-of-magnitude agreement and permit evaluation of the rate of production of neutrons in the atmosphere. This is found to be roughly 5×10^{-2} per gram per second at the level corresponding to two meters of water-equivalent below the top of the atmosphere. Recently it has been found that the rate of production of protons [2] as measured by proportional counters, cloud-chambers, and photographic plates is of the

same order of magnitude as that of the neutrons. Further, the rate of increase of both proton- and neutron-intensity with altitude is about a factor of two per meter of water, which is also that of the soft component. Coincidences have also been observed between neutron-counters and shower-counters [3]. This evidence all points to the production of neutrons and protons by cascade-photons. Such photons energetically can cause photonuclear disintegrations if the photon-energy is above a few Mev. The cross-section is known from the experiments of Bothe and Gentner [4] to increase with energy up to 17 Mev, and may reasonably be supposed to continue increasing up to several times this energy. At still higher photon-energies, say, 10^8 to 10^9 electron-volts and above, the cross-section will presumably decrease since the nuclear particles are practically free [5]. The cross-section (σ) may be computed from the relation $\sigma = (i/mNR)$, where m is the flux per cm^2 per sec of the entities producing the secondaries (neutrons, protons, or mesotrons) being discussed, i is the observed flux of these secondaries, N is the number of producing centers per cc (nuclei per cc standard air, about 5×10^{19}), and R is the range in standard air of the secondaries. If neutrons are produced by cascade-photons of energy say greater than 10^7 electron-volts, then m is 10. For neutrons, i is about one, R is 10^5 cm, and hence σ is found to be 2×10^{-26} cm^2. For protons m will also be about 10, i is observed to be 10^{-3}, R for protons with specific energy-loss sufficient to be detected by proportional counters is about one meter, and σ again is 2×10^{-26}. For mesotrons, since these can presumably only be produced by photons with energies greater than 10^8 electron-volts, m will be 2, R is 10^6 cm, i is observed to be about one, and hence σ will be 10^{-26} cm^2. These cross-sections may be compared to the value 10^{-27} cm^2 observed [4] for 17-Mev photons producing neutrons.

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AN ATTEMPT TO IDENTIFY THE SOLAR M-REGIONS

R. S. Richardson

(Abstract)

An attempt was made to identify persistent bright calcium flocculi with the solar M-regions postulated by J. Bartels to be the source of charged particles causing the 27-day recurrences in terrestrial-magnetic activity. Sketches of the bright flocculi on calcium spectroheliograms, arranged in rows of 27 days each, were compared with corresponding charts showing recurrences in magnetic activity. Identification was limited to two objectives, namely, (1) for years near minimum when bright flocculi and magnetic disturbances are scarce and therefore rendered more conspicuous and (2) for three of the most prominent sequences in magnetic activity from 1917 through 1931.

The bright calcium flocculi were found to combine the characteristics deduced for the hypothetical M-regions more completely than any other known solar phenomena, but identification was rendered doubtful by lack of agreement in certain prominent cases. The examples found where an apparently close relationship existed are probably accidental.

Since it is believed such persistent active regions could not escape detection in those portions of the solar atmosphere accessible to observation, the results obtained here indicate that the M-regions occur in a portion not readily observable--for example, below the photosphere or in the corona.

Attempts to link disturbances in the Earth's magnetic field with specific cases of sunspot-activity have usually resulted in failure. Although it has been shown that the very largest spot-groups are accompanied by great magnetic storms more often than would occur by chance, yet examples are known of magnetic storms occurring when the Sun was free from spots, and of exceptionally large spot-groups that crossed the central meridian without any terrestrial effect. On the other hand, the parallelism between the annual means for solar spottedness and terrestrial-magnetic activity is so definite there can be no doubt that some connection certainly exists.

One of the most interesting and at the same time one of the most perplexing examples of a solar-terrestrial relationship is the 27-day recurrence-period in magnetic activity. Since 27 days is also the synodic rotation-period for spots in heliographic latitude 15°, this has naturally led to the assumption that persistent active regions on the Sun produce the magnetic disturbances when they return to a certain orientation with respect to the Earth. From the behavior of the magnetic disturbances several deductions are possible regarding the nature of the hypothetical solar regions--called M-regions for convenience of reference. J. Bartels [see 1 of "References" at end of paper] has demonstrated the 27-day recurrences in a striking manner by choosing symbols for the magnetic character-figures and arranging them in rows of 27 days, each successive row beginning 27 days after the one above it. Sequences of disturbed days are thus rendered conspicuous by appearing as vertical columns having the same kind of a symbol. The "width" of a column depends upon the number of consecutive days the disturbance lasts in the successive rows.

The M-regions are subject to the following conditions:

(1) The region may remain active for ten or more rotations.

(2) It persists through months of low sunspot-activity and through days when no spots at all are visible.

(3) The width of the sequences may vary from narrow bands of two or three days up to broad columns of about a week. If the width of a disturbance is a measure of the extent of the M-region in longitude it must range from 25° to 65°.

(4) The 27-day recurrences are most prominent for moderate magnetic activity. Very large storms usually are isolated within otherwise quiet sequences.

The bright flocculi were selected as being the index of solar activity which from the detailed work of others and our own casual observations seemed most likely to meet these conditions. Bartels has already shown that there is no association between the magnetic character-figures and either sunspots or the bright hydrogen flocculi, the latter two being so highly correlated that both give practically identical results. But Luis Rodes [2] from 25 years' experience at the Ebro Observatory finds that calcium flocculi appear to be the best index of solar activity and are not highly correlated with other measures. It has also been found to give the best correlation with certain geophysical data, such as the critical frequencies of the F_2-layer [3].

Instead of using the character-figures for bright calcium flocculi already published it was thought best to refer directly to the original negatives, since otherwise some feature of significance might be missed impossible to express by a single number. A difficulty that arises in this type of investigation when examining plates individually is that one does not get the integrated effect of a large number of them and thus fails to perceive any continuity among the flocculi. This was avoided by making a sketch of the bright flocculi for each day within a circle an inch in diameter. These were arranged in rows of 27 days so as to correspond chronologically with Bartels' charts of magnetic activity. Sixteen rows were included upon a sheet.

Owing to the abundance of flocculi on the disk even several years from maximum there would be little prospect of correlating every sequence in magnetic activity with a persistent calcium cloud. For this reason, the investigation was limited to two objectives which it was believed offered the most promise of establishing the identification: (1) A comparison of the data at minimum when large flocculi are scarce and magnetic disturbances comparatively rare; and (2) study of the flocculi when three exceptionally prominent magnetic sequences were in progress. Detailed agreement in solar and magnetic activity was not required as it was felt that our ideas concerning the emission of the charged particles supposed to cause the changes in terrestrial magnetism are in general too elementary. Thus according to the usual assumptions the particles are ejected radially in a continuous stream with uniform velocity; whereas the turbulent state of the chromosphere would lead one to expect a rather irregular process of emission, with particles being shot out in blasts at all angles to the solar surface and with varying speeds.

Sketches were made for the years of minimum 1922-24 and 1932-34, and for three outstanding sequences on Bartels' chart: Days 17 to 21, July, 1918, to March, 1919, 10 rotations; days 9 to 12, November, 1921, to January, 1923, 16 rotations; days 10 to 15, January, 1930, to January, 1931, 14 rotations.

While the charts were being made it became apparent that the calcium flocculi fulfilled the four conditions stated above. Thus while a spot-group seldom lasts for more than three rotations, areas of bright flocculi were easily recognized after as many as a dozen rotations. Often brilliant clouds were found over regions which if viewed directly would have been of uniform brightness. The flocculi sometimes covered an area ten times greater than the largest spot-group ever recorded, and extended over 50° of longitude.

The most clear-cut example found of an apparent solar-terrestrial relationship occurred at the minimum of 1933 during the early part of the year. Each central-meridian passage of an unusually large bright cloud was followed within 12 to 14 days by a magnetic disturbance lasting for about a week. This flocculus was by far the most conspicuous photographed at Mount Wilson during 1933 and was especially noticeable because it was the only one on the side of the Sun turned toward the Earth. The four magnetic disturbances were all isolated within quiet days.

Excellent correspondence was also found between the sequence from July, 1918, to March, 1919, and an active region which first crossed the central meridian July 23, 1918, and made its last transit March 24, 1919. Although close to maximum of the cycle, when the disk was always covered with patches of flocculus, there was no other area during this period that endured for more than three or four rotations. The fact that magnetic disturbances are more closely correlated with calcium flocculi than with sunspots was shown very effectively on the seventh rotation when the flocculus attained maximum size and brightness. Yet on eight days of this transit across the disk no spot was near its position. In particular, on two of these days one would have been at a loss to find anything to account for the magnetic disturbance that followed a few days later, since only a single small spot was visible near the east limb. But the calcium spectroheliograms revealed a huge mass of brilliant flocculi over the southwestern quadrant of the disk.

Another sequence of nine rotations beginning on day 1 from December 5, 1919, to August 4, 1920, although not so conspicuous as the one above, corresponds remarkably well with a large flocculus that survived for eight rotations. This case is again noticeable for the fact that at the central-meridian passage of February 24, 1920, no spot occurred near the bright cloud.

After finding a form of solar activity that satisfies so thoroughly the general conditions demanded by the magnetic data as well as the particular requirements in certain outstanding cases, it is disappointing to record that in other equally outstanding examples no obvious relationship appeared. The long disturbance running from days 9 to 12 in November, 1921, to January, 1923, could not be associated with any persistent active region. This is near minimum so that identification should have been fairly easy. Likewise the highly disturbed sequence in 1930 from about days 10 to 15 had no definite counterpart on the Sun.

On the basis of this investigation it may be safely stated that the persistent active regions marked by bright calcium flocculi more closely resemble the characteristics deduced for the M-regions than any other solar phenomenon known. But owing to the absence of persistent flocculi during unusually long prominent sequences of disturbed days the writer believes the examples described above of apparently close agreement in solar and magnetic activity are accidental. Astrophysicists, however, are reluctant to accept Bartels' conclusion that the M-regions cannot be detected in portions of the Sun's atmosphere accessible to observation. Since the M-regions show no relation to spot-groups in the photosphere, and the present investigation makes it seem unlikely they exist in the chromosphere, it is suggested that they occur in a portion of the solar atmosphere not readily observable--below the photosphere or in the corona.

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DIURNAL AND SEASONAL VARIATIONS IN RADIO RECEPTION AT BROADCAST FREQUENCIES DURING THE LAST SUNSPOT-CYCLE

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At the annual meeting of the Union in 1938 a report [see 1 of "References" at end of paper] was presented showing the general inverse trend of radio field-strengths in the broadcast band with increasing solar activity. The data then presented were based upon some 800 hours of evening observations of WBBM, Chicago, received in the suburbs of Boston between 9^h to 10^h p.m. eastern standard time from November, 1935, to January, 1938.

The need for correcting field-strength observations for diurnal and seasonal variation was pointed out. It was thought that this could be expressed by a single factor which was the function of the angle of depression of the Sun below the horizon. In a subsequent publication [2] the importance of correcting radio observations for this negative solar-altitude effect was further emphasized, and a revised correction-curve published which has been regularly used at this laboratory for reducing hourly means throughout the year to a fiducial standard arbitrarily adopted, corresponding to a depression of the Sun of 30° below the horizon at the equinox in latitude 40°. Because of the wide variations in field-intensities due to the diurnal and seasonal change in the ionosphere, it is obvious that such corrections are of first consideration before fair comparisons of radio transmission are made with other cosmic phenomena.

As was pointed out, a correction depending upon negative solar altitudes as an argument should presumably make the necessary allowance for both the diurnal and seasonal range, since the angle of negative altitude (depression) of the Sun for a given latitude at a given moment involves the declination of the Sun as well as its hour-angle. It is when such corrections have been allowed for that the trend of diminishing field-intensities with increasing sunspot-numbers becomes most evident. In Figure 1 is shown the curve of increasing field-strengths in microvolts with negative solar altitude. Each point is based upon all observations corresponding to mean negative altitudes of the Sun for each even degree. The original continuous records of field-strengths are averaged by ten-minute intervals. The data utilized was based upon half-hourly means and represent altogether over 24,000 individual entries. The rhythmic oscillation at roughly 5° intervals was thought to be accidental but may be real since it shows in all attempts at representing increasing field-strengths with negative solar altitudes. No explanation for this can at present be offered. The heavy-line curve is the adopted curve for correcting for the negative altitude-effect. It has been smoothed by the process of moving averages.

If no allowance is made for such corrections as have been discussed, we should expect a marked seasonal variation presumably due primarily to the amount of illumination of the ionosphere caused by the change in the Sun's declination. Such a variation is markedly shown in Figure 2 where the mean monthly average of the night fields is plotted uncorrected for the Sun's depression below the horizon.

In addition, however, to the degree of illumination, there may be some basis for accumulative effects in ionization for which the geometrical correction for negative solar altitudes would not completely compensate. A study has therefore been made of monthly values through the years 1936-40 with the results giving evidence for such variation. In Figure 3 is the curve of mean monthly values after correcting for the angle of depression of the Sun below the horizon. It will be observed that there is a maximum in the late spring followed by an abrupt fall to a minimum value in early autumn.

The form of the curve of Figure 3 is composite and may be fairly represented by the equation

$$y = a \sin \lambda + b \cos (2 \varphi)$$

It will be observed that the first term yields one maximum and one minimum per year, whereas the second term contributes a double maximum and double minimum. The double maximum is suggestive of the form of the curve representing the well-known magnetic variation in the Earth's field.

In Figure 4 is represented the smoothed curve, a, of field-intensities of WBBM at 770 kc as received in Boston from 1936-40. The curve has been smoothed by 12-months' moving averages. A similar smoothed curve, b, for the Wolf sunspot-numbers is shown inverted on Figure 4. The third curve, c, is a smoothed curve of the mean of sunspot-areas for spots occurring in the (0° to 15°)-zones of heliographic latitude. The curve of areas is again inverted. A comparison of the curves shows a much closer correspondence between the curve of areas in the (0° to 15°)-zones

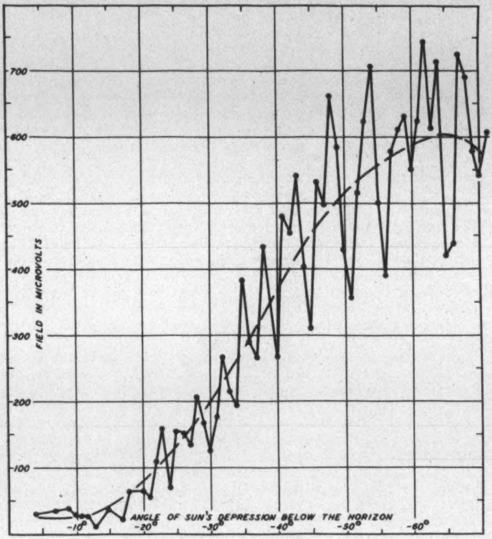

Fig. 1--Field-strength versus negative solar altitude

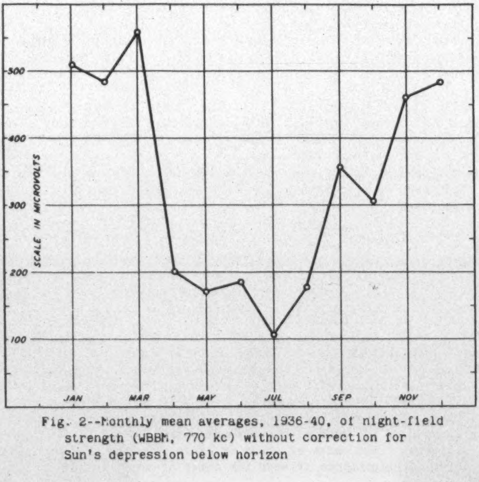

Fig. 2--Monthly mean averages, 1936-40, of night-field strength (WBBM, 770 kc) without correction for Sun's depression below horizon

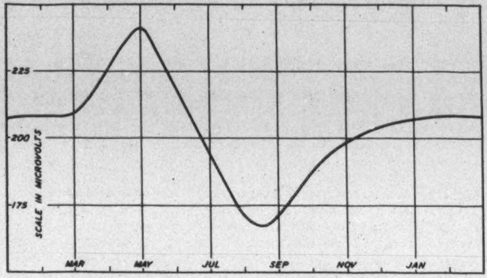

Fig. 3--Monthly mean values, 1936-40, of radio field-intensities (WBBM, 770 kc) corrected for Sun's depression below horizon

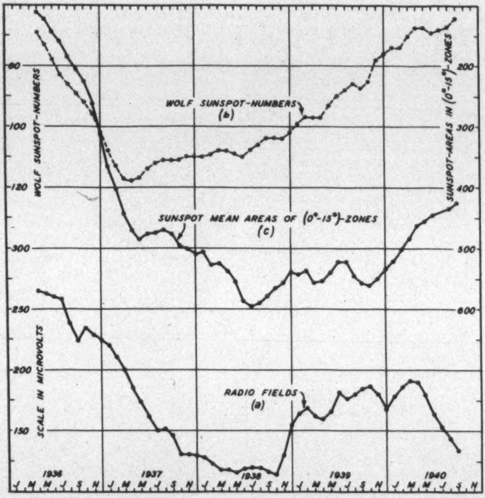

Fig. 4--Smoothed curves by 12 months' moving averages, 1936-40

than with the curve of Wolf numbers. This strongly suggests that the most active region of the Sun, so far as the effect upon radio reception at 770 kc in the path from Chicago to Boston is concerned, is the (0° to 15°)-zone either side of the Sun's equator.

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MAGNETIC STUDIES BY THE GEOPHYSICAL SECTION OF THE UNITED STATES GEOLOGICAL SURVEY

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Continued progress has been made in magnetic surveys over large sectional areas by G. R. MacCarthy. Beginning in Florida south of the Okeefenokee Swamp, magnetic traverses were measured and continued through the southern part of Georgia. The most northerly traverses crossed regions where they contacted the crystallines near the surface of the ground. All traverses were run in an east-west direction. It is planned to continue the magnetic relief-map described in the Transactions of 1939 of the American Geophysical Union by adding to it this portion of the State of Georgia.

In contrast to the large-scale magnetic surveys useful for determining regional trends, detailed magnetic studies of small areas were also undertaken. This work was for the purpose of prospecting for chrome-ore deposits. Early studies made by the writer on Oregon chrome-areas indicated that the chromite itself or the country rock immediately around it is often magnetically polarized. However, it is sometimes difficult to identify the polarization due to its variable axes relative to the Earth's magnetic field. The problem is also further complicated by the presence of magnetite which often abounds in the same area. Figure 1 shows such a magnetic traverse across a chrome-mineralized zone.

Deposits of chromite are often localized in belts or zones that occur in rocks of the peridotite group or in serpentine derived through their alteration. These belts or zones often

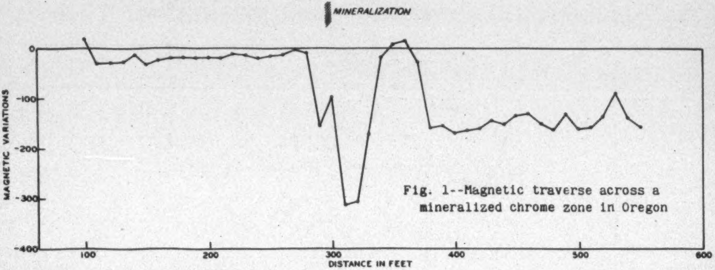

Fig. 1--Magnetic traverse across a mineralized chrome zone in Oregon

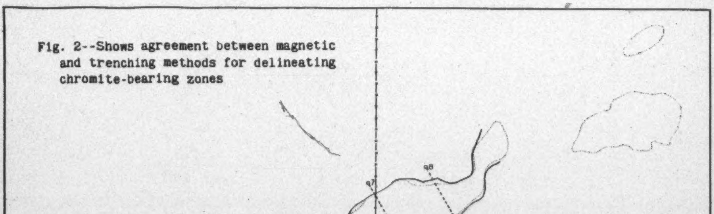
95
92
3a-1
96
97
98
EXPLANATION
Contact predicted from magnetic data
Contact found in sampling trenches
0
500
1000 FEET

Fig. 2--Shows agreement between magnetic and trenching methods for delineating chromite-bearing zones

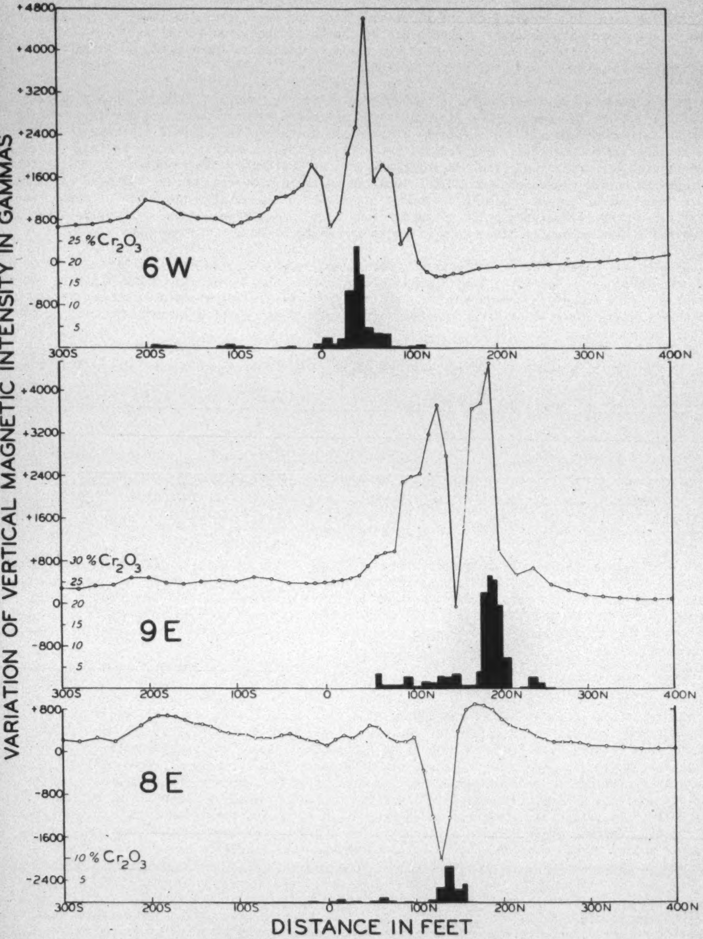

Fig. 3--Detailed magnetic traverses across chromite-bearing zone showing places of chromite enrichments

have also a distinctive magnetic character that permits the charting of their course under areas covered by a thick overburden of soil or alluvium.

Searching for chromite-ore may therefore be resolved into three separate steps:

(1) The geologic mapping of known peridotite or serpentine areas, and the indication of areas in which masses of these rocks may be concealed. A fast, cheap, geophysical method is desirable for determining the extent of such concealed masses.

(2) The magnetic surveying of the serpentine area for the purpose of locating the bands or zones in which anomalies suggest the presence of concealed bodies of chromite.

(3) Identification of the location of the chromite-bodies in these bands or zones by the combined use of magnetic and gravimetric methods.

This procedure, when applied to a chrome-area at Casper Mountain, Natrona County, Wyoming, by E. L. and H. K. Stephenson, has yielded very close correlation between the chromite-bearing areas as well as the detailed occurrences of chromite in them. In Figure 2 is shown the agreement between the boundaries of the formation containing chromite-bodies determined magnetically and by systematic trenching. The trenching was done by the United States Bureau of Mines after the magnetic survey was completed. Later detailed magnetic traverses across the zone shown in Figure 3 had characteristics similar to those in Oregon for localizing the place of occurrences of chromite. The percentages of chromite entered in this Figure were those of samples taken by the United States Bureau of Mines from trenches along the magnetic traverse-line.

As with all scientific investigations, the answer to one problem always introduces twice as many unanswered ones, and here, too, some knowledge concerning the origin of the magnetic properties of chromite would be very desirable. The relative valences of atoms of iron and chrome need some further study sinxe X-ray patterns apparently do not suffice for differentiating the magnetic properties of the mineral.

Gravimetric with magnetic surveys are now being combined in an effort to discover concealed bodies of chrome-ore.

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RESEARCHES IN TERRESTRIAL MAGNETISM AND ELECTRICITY AT DEPARTMENT OF TERRESTRIAL MAGNETISM, CARNEGIE INSTITUTION OF WASHINGTON, FOR YEAR APRIL 1940 TO MARCH 1941

J. A. Fleming

The activities of the Department of Terrestrial Magnetism in earlier years had to be directed chiefly toward obtaining field- and observatory-data, but during the period in question continued reduction and intensive study of results previously accumulated and development of attack by experiments in the laboratory, have constituted the major portion of the Department's work. Much time of personnel and an added personnel of some 70 men have been devoted to National-Defense activities.

Geomagnetic investigations

The technique of spherical harmonic analysis developed by Gauss about 100 years ago and later improved by Neumann, Schmidt, and Schuster has proved a most useful tool in the study of geomagnetism. Little attention has been given to the development of other methods of field-analysis although a number of new developments in potential-theory have appeared during the past Century in researches on hydrodynamics, heat, and sound where boundary-problems analogous to those of geomagnetism sometimes appear. Since the Gaussian method of spherical harmonics proves inadequate in certain field-problems, an investigation has been undertaken of possible alternative methods offering greater scope in general application. The fundamental limitation of the method is one of representation, a difficulty which can be overcome by the use of surface-integrals in field-analysis.

A beginning has been made in the development of a more fundamental method. Various surface-distributions of magnetic matter giving rise to the observed field have been obtained. The separation of the observed field into external and internal parts by means of surface-integrals is especially useful in the treatment of problems in which it is desirable to use data in the form of graphs instead of in analytical form. A practical general method of computing possible external or internal current-distributions capable of reproducing the observed field has not yet been found, although solutions have been obtained using the alternating process of Schwartz. The possibilities of procedures involving use of computing machines in field-analysis are also being considered.

The general theory of analysis of surface magnetic fields developed permits analysis of fields (such as those of magnetic storms) for which the method of spherical harmonic analysis is impracticable. An application to the field of magnetic storms, hitherto not analyzed for high latitudes of the Earth shows that about 60 per cent of the observed field is of external origin; departures from this value are greatest near the auroral zone. The method also affords a convenient means of estimating the errors introduced, in effecting approximate analysis, by assuming parts of the Earth's surface to be plane.

The lunar influence on the horizontal force at Huancayo Magnetic Observatory was studied in detail. Certain features of that influence were found, all of which may be interpreted by the dynamo-theory as the magnetic field of electric currents induced in the oscillating ionosphere of the Earth's permanent magnetic field. The partial tides connected with the Moon's varying distance from the Earth are clearly recognized in the geomagnetic records, but the relations of the amplitudes and the phase-angles of the geomagnetic partial tides to the main semidiurnal tide differ significantly from those in the gravitational tidal forces. The study of geomagnetic tides provides thus a new approach to the study of resonance-phenomena in atmospheric oscillations.

The attainment in March, 1940, of hydrostatic pressures in excess of 200,000 atmospheres at the Geophysical Laboratory of the Carnegie Institution of Washington, made possible further measurements of the shift of the Curie temperature. The extension of these results to some of the deep-lying constituents of the Earth's crust promises important bearing on the Earth's permanent magnetic field.

The magnetic storm of March 24, 1940, probably the greatest magnetic storm ever recorded, was an event of unusual geophysical interest. Disturbances of radio communication during great magnetic storms because of accompanying effects on the ionosphere, and the disruption of wire-communication through electric currents induced in the Earth, have frequently been noted, but during this storm the induced earth-currents attained such magnitude that electric power-systems were severely affected--the first time such effects have ever been reported. Computations were made of the intensity of currents which could be produced by magnetic changes, and for extreme cases it was found to be sufficient to produce the observed effects on power-lines. Thus, an increased practical importance of research in terrestrial magnetism has been shown, for the lengthy observations extending over a century supply definite information on the probability of occurrence of such storms and therefore on the extent to which it is advisable to revise electrical installations to avert their effects.

A study of the reduction of magnetic observations to mean of year was initiated. On the basis of the extensive data obtained during the International Polar Year 1932-33, it was found that monthly mean departures from annual mean values at magnetic observatories vary in a systematic way with geographic position, depending in a marked way upon geomagnetic latitude. The geomagnetic north component of these departures, small near the geomagnetic poles, is greatest near the auroral zones. Just outside the auroral zones this component diminishes rapidly with decreasing geomagnetic latitude and attains a secondary maximum near the equator. The changes in the geomagnetic east component are comparatively very small in all latitudes. The vertical component is large inside the auroral zone, small in middle and low latitudes, and very small or zero at the equator. These departures show a field clearly symmetrical about the geomagnetic axis and equator upon which is superposed a similar field depending locally in intensity on season of year.

The daily mean departures from monthly mean values give rise to a world-wide distribution of field of a general type similar to that found in the case of monthly departures from the annual mean. The marked dependence of these departures on geomagnetic latitude furnishes a convenient method of correcting field-observations to mean of year by interpolating the departures on the day of observation noted at a few magnetic observatories north and south of the stations. In the case of a number of days on which field-observations were made by the Department, it was found that the range in the daily mean departures from the annual mean value was as great as 45 gammas. It was further shown that if field-observations extend continuously over the entire day, in general it is possible to reduce the observed value to mean of year with a considerable degree of precision. It is hoped to include methods of reduction of mean hourly values to mean of day in this investigation.

A photographic method was developed for reducing magnetograms to common time- and ordinate-scales for all stations directly from microfilm copies of the original magnetograms for use in preparing illustrations of magnetic phenomena.

An investigation of the polar fields of sudden commencements of storms reveals that the geomagnetic north component of a commencement diminishes and the vertical component increases with increasing geomagnetic latitude in the region inside the auroral zone.

Average values of the disturbance diurnal variation, the solar daily variation, daily means of disturbance, and non-cyclic change for international disturbed and quiet days have been reduced for nearly all of the stations of the International Polar Year 1932-33. Use is being made of these data in the study of the average characteristics of geomagnetic fields.

The new measure of magnetic activity, the three-hour-range index, K, now currently derived from data obtained by seven American-operated observatories and published by Science Service, has been regularly prepared. These data have been useful in providing a detailed homogeneous series for the intensity of solar corpuscular radiation affecting the Earth, useful both in its terrestrial aspect--as in scientific and commercial radio work--and for its bearing on solar physics. In accordance with the resolution of the International Union of Geodesy and Geophysics passed at its Washington meeting in 1939, these indices are being received from magnetic observatories in other countries and are being prepared for publication regularly in the Journal of Terrestrial Magnetism and Atmospheric Electricity.

The archives of miniature-film records of magnetic registration obtained during the Second International Polar Year maintained at the Department of Terrestrial Magnetism received additional accessions. These records are now virtually complete and furnish a valuable assemblage of data which are immediately available for investigations in this country. Even if the hazardous conditions existing abroad may result in the destruction of many of the original records, the fruits of this great cooperative international endeavor to obtain magnetic records from polar regions may be preserved in these archives in the United States.

Observatory-work

The Department's observatories at Huancayo, Peru, and Watheroo, Western Australia, continued their extensive geophysical programs including determinations of the geomagnetic, geoelectric, and meteorological elements.

Cooperative work was continued with the following observatories: Atmospheric-electric and geomagnetic programs at Apia, Western Samoa; atmospheric-electric and earth-current programs at Tucson, Arizona; maintenance of international magnetic standards at the Cheltenham Magnetic Observatory of the United States Coast and Geodetic Survey; and, through the loan of apparatus, with the Cape Town Magnetic Observatory (South Africa) and the Royal Alfred Observatory (Mauritius).

Survey-work

Because of limited personnel and National-Defense activities, continuation of observations to determine secular-variation and new distribution-data have been limited largely to cooperative work with other organizations. Chief among these have been the observations made in Northern Australia and South Australia in cooperation with the Aerial, Geological, and Geophysical Survey of Northern Australia and with the Adelaide Observatory of South Australia, respectively. In Africa, in cooperation with the British East African Meteorological Service, over 30 stations--repeat and new--were occupied. Instruments were loaned and instructions prepared for magnetic work on the United States Antarctic Expedition and results were obtained at Little America. Preliminary arrangements for the loan of instruments and for instructions to observers were also made for work with the Louise A. Boyd Arctic Expedition of 1941 by which repeat-observations at CIW stations in Greenland are to be obtained.

Geoelectric investigations

From harmonic analyses of the data for the 11 years from 1924 to 1934 at the Watheroo Magnetic Observatory for potential-gradient, positive and negative conductivities, air-earth current, ratio of positive to negative conductivity, and difference between positive and negative conductivity, the 24-hour wave was found to predominate in all cases. For potential-gradient, agreement was good with the universal 24-hour wave found over the oceans from observations made aboard the Carnegie, except for the wet months May to August. The analyses show a lag of about 90 minutes for the 24-hour wave of negative conductivity as compared with that of the positive conductivity. The 24-hour wave in the air-earth current shows considerable seasonal range and its average magnitude was about that found over the oceans aboard the Carnegie.

The analysis of the diurnal variation in the vertical electric conduction-current in the atmosphere at College, Alaska, indicated a local component which is not caused by heretofore considered factors operating in the atmosphere adjacent to the Earth. That component, therefore, is thought to have broader geophysical interest than many local atmospheric-electric phenomena, some of which were subjects of investigation.

Ionization as measured with a thin-walled chamber in a closed room is less when large ions are numerous than when they are few. Tests indicate that the diminution in ionization cannot be explained on the earlier proposed hypothesis that large ions falling out of the air carry radioactive materials with them and consequently tend to clear the air of ionizing material. The phenomenon thus remains unexplained and invites additional experimental work.

An investigation of the ion-producing characteristics of ultra-violet light from a quartz mercury lamp and its application to radio fade-outs was made. The results indicate that small ions are produced in great abundance by the ultra-violet light but are promptly caught by the uncharged nuclei which also appear to be produced by the light and in this way the number of large ions may be accounted for which accompany the operation of the lamp. The fact that the small ions are formed in large numbers by the ultra-violet light of the lamp is important in the study of radio fade-outs because one may conclude that in the layer below the E-region the ultra-violet light from chromospheric eruptions produces small ions in abundance. For various reasons, it is believed that the uncharged nuclei will not be formed in this layer and, therefore, the small ions may remain in considerable numbers and thus account for the radio fade-outs accompanying chromospheric eruptions.

The small-ion content in a closed room was found to diminish when people entered the room. This appears to be due to three causes: (1) The rate of production of small ions decreases at such times; (2) the rate of destruction of small ions increases because of the increase of the number of large ions which destroy them; and (3) the average size of the large ions is increased. This increase in size and number of large ions is explained by the fact that relatively large ions are exhaled by the people present.

The resistance between the Earth and upper conducting layer through which the air-earth current flows is found to undergo a diurnal variation, the character of which is similar at Watheroo, Huancayo, and Tucson. The resistance is found to be at a minimum about 10^h local time and at a maximum about 12 hours later. The causes of this phenomenon are still under investigation.

An investigation was made of the various possible sources of error in measurement of condensation-nuclei and in particular of errors in the determination of the ratio of the uncharged to the total nuclei-content. A departure from the Poisson distribution of errors was established and several sources of experimental error were found of importance in some cases.

Ionospheric investigations

The accumulation of homogeneous ionospheric data from the Watheroo and Huancayo magnetic observatories has made detailed analysis of associated ionospheric and geomagnetic effects possible. Systematic changes in the ionosphere associated with geomagnetic activity have been found; these are not the same at different latitudes. Even small fluctuations in geomagnetism are accompanied by associated changes in ion-density in the ionosphere at both observatories. Introduction of the new three-hour-range index, K, of geomagnetic activity facilitates the investigation of systematic changes. This investigation is the first step in separation of individual factors which are involved in the complicated changes in the outer atmosphere.

Publications

The activities of the Department are set forth in greater detail in Year Book No. 39 of the Carnegie Institution of Washington. A few of the papers published during the last year are listed below:

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Washington, D. C.

MAGNETIC WORK OF THE UNITED STATES COAST AND GEODETIC SURVEY FROM APRIL 1940 THROUGH MARCH 1941

N. H. Heck

General

Despite the necessity for handling an ever-increasing volume of special work in connection with national-defense activities, the United States Coast and Geodetic Survey has maintained satisfactorily its regular program of magnetic field-work, office-reductions, and instrumental-development projects.

Magnetic surveys

The immediate goal of the field-program for the year has been the completion of the necessary magnetic repeat-observations at stations in the United States and Alaska to provide the necessary data for the preparation of two publications, "Magnetic declination in the United States in 1940" and "Alaska magnetic tables and charts for 1940." This goal has been realized. During the period, magnetic observations were made at 283 stations distributed in accordance with Table 1.

Table 1--Repeat observations

State or Territory	Old		New	
	Declination only	Complete observations	Declination only	Complete observations
Alabama	3	..	..	..
Alaska	3	2	..	1
Arizona	4	..	..	..
California	9	1	..	2
Connecticut	1	..	..	..
Florida	..	1	..	..
Georgia	4	..	..	..
Idaho	3	..	..	..
Indiana	..	..	..	1
Louisiana	3	1	..	..
Maine	5	1	..	2
Maryland	..	..	..	1
Massachusetts	2	..	1	1
Minnesota	1	1	..	..
Mississippi	2	..	..	..
Missouri	..	1	..	..
Montana	3	..	..	..
Nevada	3	1	..	1
New Hampshire	1	..	..	1
New Jersey	3	..	..	..
New Mexico	3	1	..	..
New York	2	..	..	..
North Carolina	4	1	..	..
North Dakota	..	2	..	..
Oklahoma	..	1	..	..
Oregon	1	1	..	..
Pennsylvania	1	..	..	..
Rhode Island	1	1	..	..
Texas	9	1	..	2
Vermont	7	1	..	..
Virginia	3	1	..	1
Washington	..	1	..	2
Wisconsin	2	..	..	..
Totals	83	20	1	15

Table 2--Non-repeat observations

State or Territory	Declination only
Alaska	57
California	3
Florida	7
Maine	2
Maryland	1
Massachusetts	5
New Hampshire	4
New York	9
Ohio	1
Pennsylvania	2
Vermont	8
Washington	65
Total	164

Observatories

The five magnetic observatories maintained by the Bureau operated continuously throughout the year.

Cheltenham--At Cheltenham the insulation of the east absolute wing, inaugurated in March, 1940, was completed although thermostatic control-equipment for the maintenance of constant temperature has not yet been installed. These modifications were made in anticipation of the installation of the new electromagnetic absolute instrument now being constructed by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. However, national-defense activities have resulted in an indefinite postponement of the completion of this equipment. Nevertheless, improved temperature-control has aided in securing more consistent absolute observations, especially standardizations, in the east wing at Cheltenham. At the time this wing was being insulated several modifications were made in the pier layout, including the addition of a subfloor pier with suitable non-magnetic fittings to permit setting up instruments carried on tripods.

Early in June, 1940, absolute declinometer 26 was replaced by magnetometer 37 as the Observatory's standard declination-instrument, although the corresponding change in base-line values will probably be deferred until January 1, 1941. During January, 1941, a comparison was made between Carnegie Institution of Washington earth-inductors 6 and 48. The former was later substituted as the Observatory standard while the latter was being overhauled in the instrument-shop of the Department of Terrestrial Magnetism.

In June, 1940, insensitive la Cour D- and H-variometers were set up in the variation-building. The Adie Z-variometer had already been operated as an insensitive instrument for a number of years. As a result of this installation complete records have been obtained of all magnetic storms since June, 1940, including the severe storm of March 1, 1941, when approximate ranges were recorded as follows: D, 2 3/4°; H, 1370γ; Z, 760γ.

Honolulu--No important changes were made at the Honolulu Observatory although a determination of station-differences for declination and horizontal intensity between the regular and auxiliary absolute piers was made with a new transit-magnetometer. Final results of this work are not yet available.

Sitka--At Sitka the magnetograph continued operation in the temporary variation-building although plans are now being made in Washington to supply new sensitive and insensitive magnetographs for installation in the permanent variation-building as soon as possible.

San Juan--At San Juan a sealed cover for the variometers for humidity-control was completed and installed and is apparently operating fairly satisfactorily.

Tucson--At Tucson an intercomparison program for declination and horizontal intensity between that Observatory and Cheltenham was carried out in the late fall of 1940. At that time magnetometer 31 replaced 30 as the Observatory standard. During the year a new magnetograph, which is described in a paper by J. H. Nelson and A. K. Ludy published in these Transactions, was set up in the test-laboratory at Cheltenham. After several months of successful operation it was shipped to Tucson for installation in the new variation-building. This instrument should be in routine operation some time during the summer or fall of 1941.

Cooperative work

Through the cooperation of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, the following projects have been continued:

(a) Use of the sine-galvanometer and the standard earth-inductor of the Department of Terrestrial Magnetism at Cheltenham.

(b) At Cheltenham the cosmic-ray meter of the Committee on Coordination of Cosmic-Ray Investigations of the Carnegie Institution of Washington operated continuously throughout the year. A second meter was installed and operated for a period of several months. It was then dismantled and removed.

(c) Standardization of field-instruments of the Department of Terrestrial Magnetism was carried out at Cheltenham by personnel of that organization.

(d) The atmospheric-electric program at Tucson was continued throughout the year and also the earth-current program with the additional cooperation of the Mountain States Telephone and Telegraph Company and the American Telephone and Telegraph Company.

(e) The assignment of additional three-hour-range indices was made for observatories of the United States Coast and Geodetic Survey and the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for various periods prior to 1940. This included Cheltenham records for 1929-30, done in an effort to clarify if possible certain discrepancies in the correlation between the international character-figure and Bartels' interdiurnal variability-measure (u-measure) for that period.

Through the cooperation of Science Service and the Navy Department, daily Ursigram messages giving magnetic conditions at Cheltenham including the three-hour-range indices (K-measure) were distributed. Weekly summaries of the daily Ursigrams and K-numbers for all five observatories of the Coast and Geodetic Survey and the two Carnegie Institution of Washington observatories are included in the Science Service Research Aid Announcement which is available at no cost to interested investigators.

Routine and special reports of magnetic conditions were supplied the National Bureau of Standards, the Carnegie Institution of Washington, and various interested persons. This included making magnetograms available for reproduction by photostat- and microfilm-processes.

Miscellaneous projects and investigations

The assignment of three-hour-range indices was continued for the periods prior to 1940 until at the present time a complete series from 1937 to date is available for Cheltenham and Sitka, from 1938 to date for San Juan and Tucson, and from 1940 to date for Honolulu, and at the latter Observatory the first half of 1938 has also been assigned.

During the course of the year, the Bureau has been called on for numerous special projects in connection with national-defense activities. Several of these involved magnetic work, and considerable time and effort have been devoted to such projects.

Office work and the reduction of records

Through aid obtained from the Work Projects Administration Computing Office in New York, the reduction of observatory-records for the Polar-Year period has been continued under the direct supervision of Bureau personnel. The period 1931-32 is now about complete for all observatories except San Juan with the exception of the preparation of the descriptive portion of the manuscript. Work is now being performed on records of 1933-34 for all observatories. During the period, some check scaling work on San Juan records was carried on as a Work Projects Administration project at the San Juan Observatory.

At present, the Washington Office is giving priority to the preparation of the two publications "Magnetic declination in the United States in 1940" and "Alaska magnetic tables and charts for 1940." It is hoped that the former will be in print some time before the fall of 1941, and the latter early in 1942. The charts included in the publications may precede the actual publications by a month or two if practicable.

As usual, the Washington Office continued to supply magnetic data for the various nautical and aeronautical charts issued by the United States Coast and Geodetic Survey. In regard to nautical charts, special attention has been devoted to the investigation of regions of magnetic anomalies, and where possible to obtain them, additional field-observations have been obtained for such regions. A start has been made on a practical study of magnetic anomalies in the air, with special reference to the data depicted on aeronautical charts.

Personnel

It is with extreme regret that we announce the death of Lieutenant Commander G. C. Jones on August 15, 1940, while at his post of duty as Officer-in-Charge at San Juan. Following this, the San Juan Observatory was taken over temporarily by Commander H. A. Cotton, who in turn was replaced by Lieutenant Commander Ray L. Schoppe on November 27, 1940.

At Honolulu, Lieutenant Earl O. Heaton completed his assignment at the Station and was relieved by Lieutenant Benjamin H. Rigg on March 4, 1941. At Tucson, R. F. White replaced John

Hershberger as Observer-in-Charge on July 1, 1940.

On March 31, 1941, George Hartnell retired from active duty in the United States Coast and Geodetic Survey after 33 years of service, 30 of which were spent at the Cheltenham Observatory. During that period he made many valuable contributions in the field of geomagnetism and his loss to the Bureau will be keenly felt.

U. S. Coast and Geodetic Survey,
Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30 – MAY 3, 1941

7

SECTION OF OCEANOGRAPHY

REPORTS AND PAPERS

WASHINGTON, D. C.
MAY 2, 1941

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Reports and Papers, Section of Oceanography
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9:00 A.M., May 2, 1941

OCEANOGRAPHIC ACTIVITIES OF THE UNITED STATES COAST AND GEODETIC SURVEY

L. O. Colbert

The oceanographic activities of the United States Coast and Geodetic Survey have continued, primarily in the survey of areas in United States waters and in its possessions. Modern methods of hydrographic surveying introduced by the Bureau have required observations of temperature and salinity to determine the velocity of sound in sea-water in each area under survey for correcting echo-soundings and for determining horizontal distances in position-finding by radio-acoustic ranging. These data are also of interest to the oceanographer.

The Survey has continued the cooperation of collecting bottom-specimens in the Gulf of Mexico, started last year for the Houston Geological Society. During the past season the Survey Ship *Hydrographer* collected specimens in the eastern part of the Gulf for the Department of Geology of the University of Florida.

The new ships, *Explorer* and *E. Lester Jones*, which were completed last spring, had very successful seasons in the Bering Sea. Two additional ships are now under construction at Seattle. The smaller, a wooden vessel 88 feet long, will be completed next fall; the larger steel ship, 230 feet in length, will be completed in the fall of 1942. These vessels will also be assigned to Alaskan surveys.

For the past several years all survey ships en route to and from the Alaskan working grounds have run sounding lines across the Gulf of Alaska. This work has progressed now to the point that lines are now run only when southbound. In addition, the ships operating in the Aleutian Islands at convenient times during the season run sounding lines across the Aleutian Trough as the survey of this chain progresses to the westward. Following is a brief résumé of the work of the ships last season:

On the Atlantic Coast the *Oceanographer* extended surveys in the Gulf of Maine from the coast of Massachusetts offshore about 150 miles for a completed width of about 70 miles. This survey was rigidly controlled by a system of radio-acoustic-ranging triangulation, strengthened along the full length of the south side of the scheme by taut-wire measurements between buoys, with several cross-ties. At the end of the season a connection was made on the northeast tip of Georges Bank with the survey in that area made in 1930. The United States Coast Guard cooperated at the end of the season by placing two navigation-buoys on the Bank to mark the end-positions of a base from which to continue this survey further offshore another season. An intensive survey was required to cover the rugged bottom found. The characteristics of this uneven bottom in the Gulf of Maine may be readily identified and when charted will serve as aids to the mariner for determining position.

The *Lydonia* and *Gilbert* were engaged on surveys of Nantucket Shoals. During the latter part of the season the *Lydonia* took up surveys in Massachusetts Bay.

In the Gulf of Mexico the *Hydrographer* continued offshore surveys between the Mississippi Delta and Pensacola. On this work, it was necessary to locate two RAR stations in deep water. One survey buoy was placed in 1,050 fathoms and another in 1,350 fathoms. Stainless steel wire, 3/16 inch, with 800-pound anchors, composed of several discarded car-couplers were used in mooring these buoys. Upon completion of the stations, the anchors were detached by a special apparatus and only the buoys and wire mooring-gear recovered.

During the summer season, the *Explorer*, *Pioneer*, and *E. Lester Jones* operated in the Aleutian Islands in the vicinity of the Islands of the Four Mountains; the *Guide* along the north coast of the Alaska Peninsula; the *Discoverer* along the south coast of the Alaska Peninsula; the *Surveyor* on the coast between Lituya Bay and Dry Bay; and the *Westdahl* in Glacier Bay.

During the winter season, the *Explorer* and *Surveyor* operated in the Strait of San Juan de Fuca and the *E. Lester Jones* and *Westdahl* in the San Juan Islands, Puget Sound. The *Discoverer* made surveys in Grays Harbor, Washington. The *Guide* operated part of the season in the vicinity of Cape Mendocino and part in the revision surveys of San Francisco Bay. The *Pioneer* extended geodetic control in the islands off the California Coast early in the winter season and later was engaged on revision surveys in San Francisco Bay.

These Pacific Coast vessels have again sailed for the Alaskan working grounds. They will resume work in the same general vicinity as they were engaged during the previous season, except that the Westdahl has been shifted to a survey of the approaches to Sitka, the E. Lester Jones to Cook Inlet and Kodiak Island. The Surveyor will survey Yakutat Bay and approaches early in the season and then proceed to the vicinity of Passage Canal, Prince William Sound. After the close of the present Alaskan season, the new Explorer will be assigned to surveys in the Hawaiian Islands in the vicinity of Laysan and Midway Islands.

In the Philippine Islands, the Pathfinder and Fathomer continued operations in the Sulu Sea. A taut-wire sun-azimuth traverse was run along a line of survey-buoys extending from a station located on the Palawan datum by observations on mountain peaks to a station at the other end of the traverse connected with the Cagayan Sulu Island triangulation. This traverse connected the two datums without resort to triangulation along the north coast of Borneo and proved entirely satisfactory for all charting purposes.

Recently two officers on the Ship Explorer developed a radio current-meter which will permit automatic observations of currents from a special survey-buoy placed on station in a manner somewhat similar to our radio-acoustic-ranging stations. The current-meter was further improved during the past winter, and several units are now under construction for use in Alaska this summer. By means of this apparatus, the velocity and direction of the current are automatically broadcast by the radio set installed within the buoy and are recorded on the chronograph tape on the survey ship. The radio buoys broadcast on slightly different frequencies, each buoy in turn. It is believed that this current-meter which will be known as the Peters-Roberts Radio Current-Meter for the two officers directly responsible for its development, will mean a marked advance in the determination of ocean-currents. A full description of the meter will be contained in the next Field Engineers Bulletin of the United States Coast and Geodetic Survey.

In the field of tides, the Survey's system of tide-stations was continued in operation. This network of stations is undergoing gradual expansion as facilities permit, with a view to increasing the scope and usefulness of the observations. Eighty-two stations are now in operation with six more in process of installation. Records from these stations are becoming increasingly valuable as the basic source for comprehensive tide-data.

For several years past the Survey has carried on special tide-surveys covering various coastal waterways. The surveys of the Sacramento-San Joaquin Delta Area and the Connecticut River were completed last year and this year a survey of the Columbia River tides has been inaugurated.

Following its policy of standardizing methods of tide-observations and of obviating duplication of effort, cooperation was continued with various Federal and State agencies as well as with private interests, port authorities, and oceanographic institutions. Organizations which have furnished facilities and personnel for cooperative tide-observations include the Army Engineers, Navy, Coast Guard, Weather Bureau, Scripps Institution of Oceanography, the Oceanographic Laboratories of the University of Washington, the Chesapeake Biological Laboratory, and the Woods Hole Oceanographic Institution. The observations at the primary tide-stations at Key West, Miami Beach, Cat Cay, and Charleston have been used by the Woods Hole Oceanographic Institution in a study of the correlation of the flow of the Gulf Stream with changes in sea-level.

In accordance with cooperative arrangements between the United States Government and governments of some of the other American Republics, tide-stations have been established in Mexico, El Salvador, Costa Rica, Colombia, Venezuela, Ecuador, Peru, and Chile. The Survey has supplied instrumental equipment and its representatives have practically completed the installation of the stations in those countries.

The publication of annual tide-tables is another oceanographic function of the Bureau. In the 1941 tables, Bergen, Norway, is included as a new reference-station. In the 1942 tables, Bridgeport (Connecticut), Reedy Point (Delaware), and Bangkok Bar (Thailand) will be included. A revised edition of the "Manual of the harmonic analysis and prediction of tides" has been published.

In the field of currents, the hourly direction and velocity of the currents in Narragansett Bay, Buzzards Bay, Vineyard Sound, and Nantucket Sound are depicted in a new publication, "Tidal current charts, Narragansett Bay to Nantucket Sound." On the basis of observation data supplied by the Army Engineers, revised predictions have been made of the currents in the enlarged Chesapeake and Delaware Canal.

Continuous hourly observations of the velocity and direction of the current covering a period of more than a year have been made at Overfalls Lightship through a cooperative arrangement with the United States Coast Guard. A similar series at Portland Lightship is now under way and steps are being taken to start observations at Frying Pan Shoals Lightship. During the past 30 years, at more than 50 lightship locations distributed along our Atlantic Coast, series of current-observations have been taken varying in length from a few months to several years. The results derived from these observations will be published in the near future.

In closing I want to express my appreciation of the valuable assistance given by other organizations in furthering the work of the Survey.

U. S. Coast and Geodetic Survey,
Washington, D. C.

RECENT OCEANOGRAPHIC WORK BY THE HYDROGRAPHIC OFFICE OF THE UNITED STATES NAVY

G. S. Bryan

While the work of the Hydrographic Office and the United States Navy has been vastly increased, due to the present national emergency, the oceanographic activities have necessarily been severely curtailed. You may be interested to know that the production of our nautical charts has increased 500 per cent over normal times, due not only to the large number of additional naval vessels, but also to the ever-increasing dependence of the maritime world upon the Hydrographic Office for charts and publications heretofore obtainable from foreign sources. My report is therefore short and general in scope.

In furtherance of its program of adequately charting those areas in South and Central American waters which are important commercially and strategically, particularly due to their relation to the Panama Canal, the Hydrographic Office carried out surveys, during the past year, in Venezuela and Ecuador. In addition, special surveys were also conducted covering some of the newly acquired naval bases.

During the present season, in addition to considerable other survey work it is planned to complete the survey of the north coast of Venezuela from Margarita Island eastward to Punta Penas, thus completing the hydrographic charting of the coasts of Venezuela, and practically completing that of the entire north coast of South America. To expedite this work, and because of the nature of the terrain, ship-shore triangulation will be utilized.

I am pleased to report that the vast amount of accumulated sonic-sounding data, referred to in my last report to the Union, have now been plotted and correlated, and that their incorporation on affected charts is progressing as rapidly as practicable. These data covering a total of 290,000 nautical miles over heretofore unsounded areas, involving over 1,000 separate reports, will be of great value to the mariner and to scientists in general. It is interesting to note that 54 per cent of the soundings relate to the North Atlantic Ocean and that 42 per cent refer to the North Pacific Ocean. The remaining four per cent cover the other oceans. Half of the soundings in the North Pacific area were obtained by the U.S.S. Ramapo.

In the Caribbean Area, the U.S.S. Hannibal conducted a well-controlled development of the Bonaire and Cariaco trenches, the details of which will be published on the new charts of this area which will be available for issue early in 1942.

Since the publication of the Bathymetric Chart of the Caribbean Sea (H.O. Chart No. 5487), considerable new data have been secured by United States Naval Vessels which will lead to modifications in the bathymetric contouring of some of the areas (Fig. 1).

Particularly in the region around Puerto Rico, additional information is now available to the scientist which may modify or revise some of their conclusions regarding the formation of the geologic structure of that section in the Antilles.

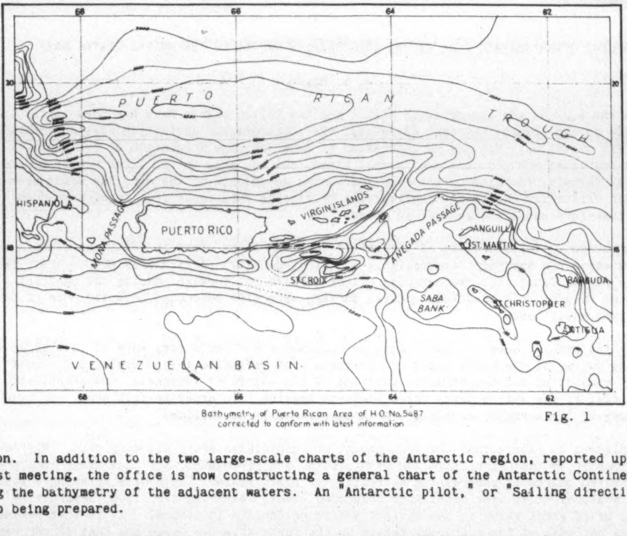
It is hoped that, in the near future, additional sounding data will be available for the Virgin Islands Area to fill the gaps which still exist. It is also expected that our prospective surveying program will include the taking of a number of additional soundings in the vicinity of

Milwaukee Depth, the deepest point in the Atlantic as far as present knowledge goes.

During the past year, the U.S.S. Northampton and the U.S.S. Salmon discovered several banks southwest of Laysan Island and Pearl and Hermes Reefs in the Hawaiian Chain. These banks, with surrounding waters of 1,000 to 2,000 fathoms, were found to have least depths of 17 and 30 fathoms, respectively.

While it has not been possible to install an oceanographic laboratory aboard the new survey survey vessel Bowditch, she has been equipped with a dynamic sounding-winch, water-bottles, and deep-sea reversing thermometers. Plans were made to conduct a series of dynamic surveys off the west coast of South America between Panama and Guayaquil, but the acquisition of new naval bases required the presence of the Bowditch in other areas. These dynamic surveys, however, will be made when opportunity affords.

The Hydrographic Office has continued its cooperation with the United States Antarctic Expedition. In addition to the two large-scale charts of the Antarctic region, reported upon at the last meeting, the office is now constructing a general chart of the Antarctic Continent, including the bathymetry of the adjacent waters. An "Antarctic pilot," or "Sailing directions," is also being prepared.



Bathymetry of Puerto Rican Area of H.O. No.5487
corrected to conform with latest information

Fig. 1

This year marks the completion of a project commenced in 1936 for the evaluation of ocean-currents and sea surface-water temperatures. Originally undertaken to include only the North Pacific Ocean for a ten-year period, the success of the undertaking prompted the Hydrographic Office to enlarge its scope to include all oceans and embrace all material available covering a 30-year period. The accomplishment of this project furnishes the Hydrographic Office with over five million observations, tabulated by months, listing all surface-water temperatures, currents, wind-forces, and wind-directions, for each one-degree quadrangle of the Atlantic, Pacific, and Indian oceans. From these data the Hydrographic Office will be enabled to compile monthly temperature-charts showing the maximum, minimum, and average surface-sea-water temperatures of the various oceans and to produce ocean-current charts that will assist materially in bringing up to date the existing publications of the office. All these data will be available to the scientific world and should prove of inestimable value in solving the many existing problems relating to oceanic circulation, atmospheric and climatic conditions, and other related questions in oceanography.

In these times of national emergency, science is playing an important role in the solving of National-Defense problems. The various institutions represented here are cooperating to the fullest with the United States Navy on questions involving oceanography, meteorology, and other

sciences. This assistance is greatly appreciated, and I wish to assure the Union that the cooperation is mutual. Facilities and services of the Hydrographic Office are always at the disposal of members in the furtherance of their studies.

U. S. Hydrographic Office,
Washington, D. C.

OCEANOGRAPHIC WORK OF THE UNITED STATES COAST GUARD IN THE WESTERN NORTH ATLANTIC IN 1940 AND PLANS FOR 1941

R. R. Waesche

During 1940, because of the almost total absence of ice in the vicinity of the Grand Banks of Newfoundland, only one ice-observation cruise was made by the U.S.C.G. cutter Chelan in connection with the International Service of Ice Observation and Ice Patrol in the North Atlantic Ocean. Consequently, the usual ten or a dozen fortnightly sea-surface isothermal charts of that area were not made. However, in anticipation of the possible southward drift of menacing ice, the 125-foot cutter General Greene, operating as the oceanographic vessel of the Ice-Patrol Force, repeatedly surveyed the Grand Banks Region during April, May, and June. As the third survey involved going over the same area twice in as rapid succession as possible, five dynamic topographic charts resulted from the four surveys. These charts were referred to the 1,000-decibar surface although at most of the 235 oceanographic stations occupied the temperature- and salinity-measurements extended to a depth of about 1,400 meters where the depth of the water permitted. From June 25 to 29 the General Greene occupied an additional 21 oceanographic stations from the surface to as near bottom as was practicable on a short post-season cruise in the Labrador Sea between South Wolf Island, Labrador, and Cape Farewell, Greenland. These stations were disposed in the form of a single section crossing the Labrador Current, the central Labrador Sea, and a part of the West Greenland Current. Unusually extensive sea-ice off the Greenland Coast prevented the complete crossing of the West Greenland Current. Incidental data collected on the General Greene both during the season and post-season cruises consisted of barograms and sea-surface thermograms.

Between September 14 and 17, 1940, the cutter Northland occupied 13 oceanographic stations on the western side of Baffin Bay. These stations were disposed in the form of two sections approximately normal to the trend of the Baffin Land Coast and reaching from coastal waters to positions of 73° 10' north, 68° 30' west, and 70° 41' north, 64° 23' west. At each of these 13 stations serial observations of temperature and salinity extended from the surface to as near bottom as was practicable under the circumstances, the greatest depth of observation being 1,861 meters. An additional single station was occupied by the Northland on December 21 in the north-central part of the Labrador Sea to a depth of 3,234 meters. Although still about two months prior to the coldest time of year, this is the first approach to mid-winter observations in the area considered in United States Coast Guard Bulletin 19, part 2, to be a source of bottom-water of North Atlantic.

The scientific work undertaken on the Northland was under the direction of Commander Edward H. Smith, U.S.C.G., and Dr. C. A. Barnes, that on the General Greene was under Floyd M. Soule, and that on the Chelan was under the Ice-Observation-Officer, Lieutenant W. P. Hawley. United States Coast Guard Bulletin No. 30, by Hawley, Smith, Barnes, and Soule, is now in press. This Bulletin deals with the results of the work of 1940 just outlined. The section of this Bulletin on the oceanography of Baffin Bay is abstracted as follows:

(1) New oceanographic data obtained in a previously uninvestigated area in the western part of Baffin Bay have been presented.

(2) The dynamic topography, bottom-topography, and characteristics of the Baffin Land Current in this area have been discussed.

(3) The circulatory system of Baffin Bay waters has been reviewed considering the new data and with emphasis on the role played by the Baffin Land Current.

(4) The characteristics of Baffin Bay water have been compared to those of the water of the Labrador Sea south of Davis Strait Ridge, and the interchange of water between these two bodies has been discussed.

The section on the oceanography of the Grand Banks Region and the Labrador Sea is summarized as follows:

(1) The four surveys resulting in five maps of the Ice-Patrol area in the vicinity of the Grand Banks, made during the season of 1940, have been described.

(2) The seasonal variation in the Labrador Current in the Grand Banks Region during 1940 has been compared with other variations found during the previous six ice-seasons on the basis of minimum observed temperature, mean temperature, and volume of flow computed for each occupation of each of three sections.

(3) Temperature-salinity correlations for the three types of water found in the Ice-Patrol Area, Labrador Current water, mixed water, and Atlantic Current water have been investigated for each survey of the region made during the seven-year period 1934-40, and mean curves have been presented comparing conditions in 1940 with the seven-year means.

(4) A new criterion of the boundary between the Atlantic Current water and mixed water or Labrador Current water has been selected and the boundary delineated for each survey made during the seven-year period 1934-40. Fluctuations in the position of this boundary east of the Grand Banks have been considered by studying the fluctuations in an area enclosed by arbitrarily fixed lines on three sides and the current-boundary on the fourth side. A mechanism has been set up for quantitatively separating the boundary-fluctuations caused by the Labrador Current from those arising from causes affecting the Gulf Stream system.

(5) An apparent relationship found between fluctuations in the difference in sea-level, Bermuda to Charleston, and the volume of flow of the West Greenland Current at Cape Farewell, Greenland, one year later has been described and two possible explanations offered.

(6) Abnormal thermal conditions found in the intermediate water between southern Labrador and southern Greenland on the 1940 post-season cruise substantiate the picture of the formation of deep- and bottom-water in the Labrador Sea described in United States Coast Guard Bulletin 19, part 2, and are discussed in the light of that hypothesis.

(7) The volume of flow, mean temperature, and heat-transfer of the Labrador Current at South Wolf Island have been computed from measurements made during 1940 and compared with the results of eight previous occupations of this section. Attention has been called to the connection between low values of mean temperature and heat-transfer at this section and small numbers of bergs reaching the Grand Banks, and the significance of departures from normal barometric pressure-gradients in the vicinity of Davis Strait pointed out.

In view of the present international situation, the United States Coast Guard and the Woods Hole Oceanographic Institution have jointly undertaken the preparation of a batch of standard sea-water similar to that prepared by Dr. Knudsen in Denmark. Much of the preliminary work has been done and it is hoped that this new standard water will be available before existing stocks of Knudsen's batch P_{15}, now on this side of the Atlantic, are exhausted.

The oceanographic work planned for 1941 is already in progress. The General Greene completed the first survey of the Grand Banks Region on April 18, 1941, after occupying 85 oceanographic stations. It is expected that two additional surveys will be made of the Grand Banks Region, followed by a short post-season cruise between southern Labrador and southern Greenland. Other plans, such as detailed observations in the immediate vicinity of an iceberg under various conditions of wind and sea are supplemental to the main program of surveys and contingent upon convenient circumstances.

U. S. Coast Guard,
Washington, D. C.

FINE STRUCTURE OF THE EDGE OF THE GULF STREAM

Athelstan F. Spilhaus

(Abstract)

(Contribution No. 290 of the Woods Hole Oceanographic Institution)

Purpose--The purpose of the following investigation is to obtain a detailed description of conditions in a region of great lateral shear and to attempt to represent synchronous conditions on surfaces in a lateral plane.

Previous indications--Two sections through the edge of the Gulf Stream made in 1939, namely, (a) with the bathythermograph (July) and (b) with the bathythermograph and pressure-operated sea-sampler (August), had shown, from (a), a complex temperature-structure suggesting the presence of eddies and, from (b), that the complex temperature-structure was the result of lateral juxtaposition of different water-types probably by eddying motion [see 4 of "References" at end of paper].

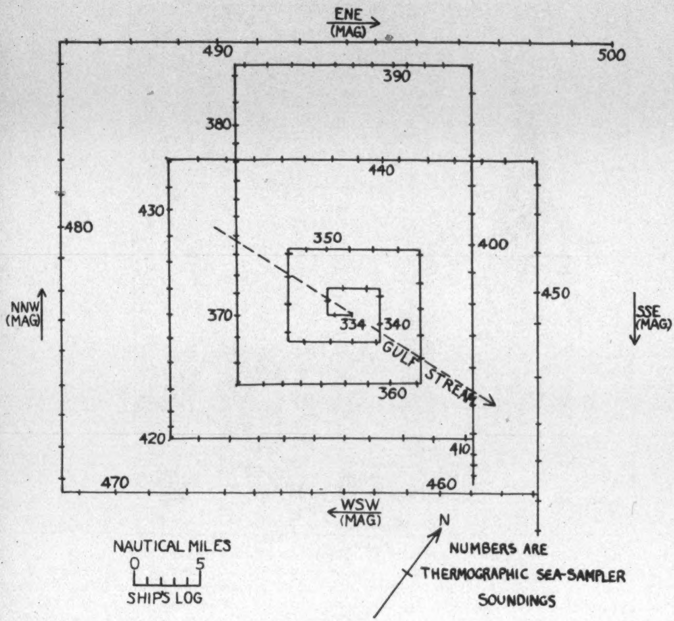


Fig. 1--Ship's run

Choice of region--The neighborhood of the Gulf Stream is chosen because eddies will be found where there is great lateral shear. To identify these eddies most easily the region was selected where horizontal temperature-gradients are greatest. The "edge" of the Stream as defined in this way (by the region of greatest horizontal temperature-gradient) is well within the boundary defined by the velocity. (Observations by Church in 1937 [1] of surface-temperatures give a far narrower "stream" than that, for instance, Iselin in 1936 [2] defined on the basis of where the velocity falls to ten cm per second.)

The region was located on the outward course by making a section by the regular hydrographic technique down to about 1,000 decibars. The edge of the Stream was identified and the vessel taken well into the Stream. The course was then retraced using the bathythermograph continuously and the starting point for the detailed investigation was thus selected (about latitude 37° 40' north and longitude 69° 10' west). Starting at this point, a run was made by log and compass as in Figure 1.

Instrument--During the whole run, soundings were made continually with a new instrument, the thermographic sea-sampler. This instrument is a combination of the bathythermograph and pressure-operated sea-sampler [4] using a single pressure-element. It is used just as is the bathythermograph, while under weigh and in a single sounding provides a recorded trace of temperature against pressure and also six samples of sea-water at different predetermined pressures (I, Fig. 2). The maximum pressure for this instrument was 150 decibars; in order to reach this depth without exceeding it by much and thereby incurring the possibility of damaging the pressure-element, it was necessary to obtain an idea of the "wire-out: depth-reached" relationship for different speeds of the vessel. This was greatly facilitated by the barochronograph (II, Fig. 2) used for the purpose on an earlier short cruise. (This latter instrument, although in crude form, has been used with nets and with the Hardy plankton-recorder with interesting and useful results.)

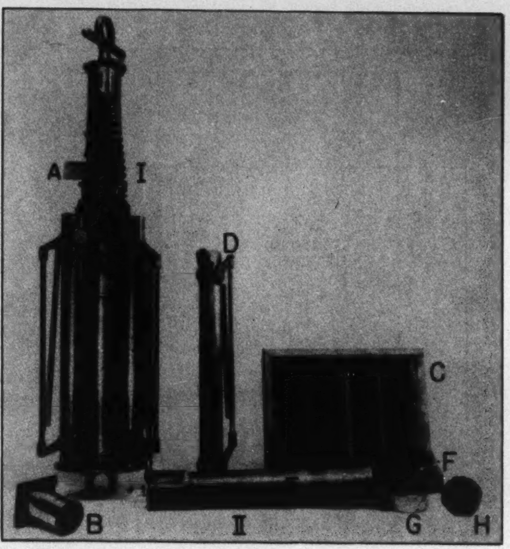


Fig. 2--(I) Thermographic sea-sampler (combined bathythermograph and sea-sampler)
[A = slide with temperature-pressure trace; B = viewer--slide A is viewed superimposed on calibration-grid, thus permitting immediate reading off of pressure-temperature data; C = box of temperature-pressure record slides; D = sample-bottle, removed from instrument, cocks closed]
(II) Barochronograph
[Pressure-element in E moves pen radially outward on octagonal slide in F, rotated by clock G; slide H shows original barochronograph-record for four soundings at different speeds of vessel]

Collection of data--While the Atlantis was executing the run which occupied three days (from August 23 to 26, 1940) up to the occurrence of a severe storm (at sounding No. 500), soundings were made on an average of one every 22-1/2 minutes, that is, every two miles corresponding to an average speed throughout the run of 5-1/2 knots.

Each sounding provided (1) a record of temperature against pressure down to 150 decibars and (2) samples of water from the surface and six other evenly spaced levels down to 150 decibars.

The samples were divided into two parts, one for oxygen-determination (carried out on board concurrently), the other stored (in special small bottles) for subsequent chlorinity-determinations.

In all, 230 thermographic sea-sampler soundings were made providing 1,610 oxygen-values and the same number of chlorinities. Of these, 200 soundings with 1,400 oxygen- and chlorinity-values were those taken in the water under detailed investigation in a period of 3-1/2 days.

Treatment of data--Thus for the surface and six other levels, pressure, temperature, chlorinity, and oxygen were known and σ_t was determined so that for a given value of σ_t, pressure was scaled off a plot of σ_t versus pressure; with this pressure, temperature was read off the original record of the instrument and the value of oxygen scaled off a plot of the seven sample-points. The temperature- and oxygen-distribution on the σ_t-surface could then be represented and the configuration of the surface, in terms of pressure, drawn. [For other analyses of conditions on σ_t-surfaces see, for example, Montgomery 1938.]

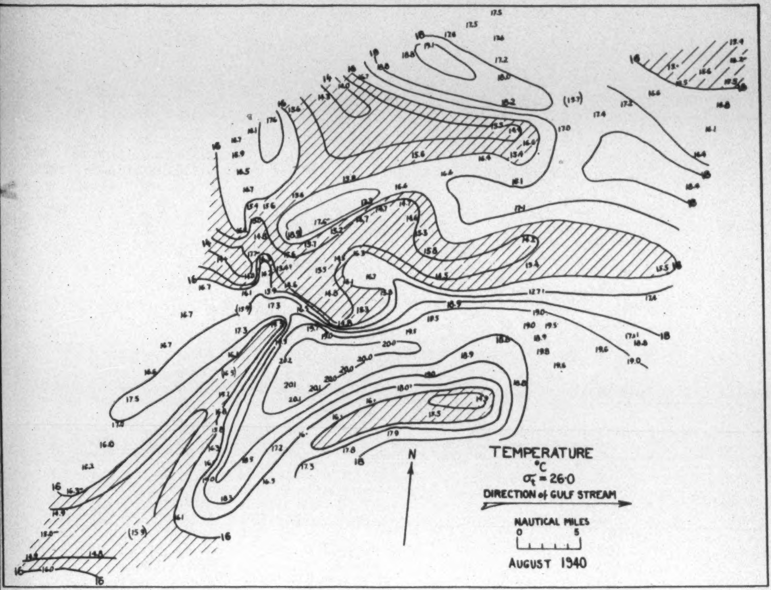


Fig. 3--Temperature-distribution on surface σ_t = 26.0

Representation of conditions on σ_t-surface--Although the new rapid-measuring hydrographic technique provides a means, with one vessel, of approximating simultaneous collection of the data, it is desirable to reduce the position of the soundings to that which would have obtained if they had been taken exactly simultaneously. The relative positions of the water-parcels encountered by the instrument were computed as they were at the time of the start of the run.

This reduction was carried out under the following assumptions:

(i) All flow parallel to the observed mean direction of the Stream.

(ii) Surface velocity-gradient constant and equal to the mean value for the region obtained by computation of velocities (relative to the 1,000-decibar surface) from the deep hydrographic section taken on the outward course. The value of the surface horizontal shear found in this manner = 10^{-5} $\sec^{-1}$.

(iii) Velocity-difference between sea-surface and σ_t-surface analyzed is constant and equal to the mean value obtained by computation as in (ii). The velocity at σ_t = 26.0 was found to be 14 cm/sec less than the sea surface-velocity in the mean.

The procedure of reduction of the position of the water-parcels to time of start of run (sounding No. 334) is then:

(i) Mean sea-surface drift is eliminated by making run by log and compass.

(ii) Ship's track relative to axes moving with surface-water at point of start of run is computed using computed mean sea-surface shear.

(iii) Water parcels encountered on ship's track in σ_t-surface are reduced to positions relative to sounding No. 334 by computed velocity-distribution in surface and elapsed time between the particular sounding and sounding No. 334.

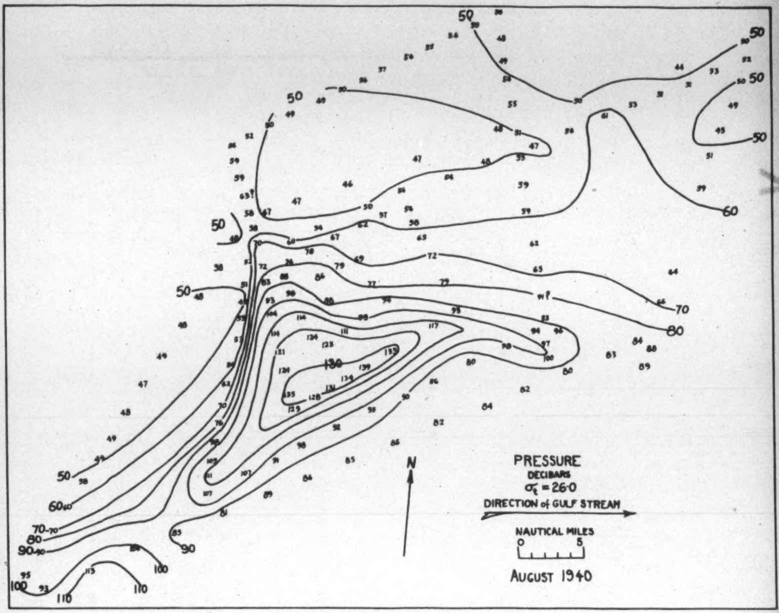


Fig. 4--Pressure-distribution on surface $\sigma_t = 26.0$

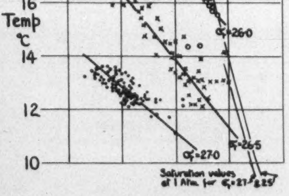


Fig. 5--Oxygen-temperature correlation on σ_t-surfaces

Reduced grid--The result of this reduction is a skewing distortion of the run-grid. Widely different values of shear and direction of Stream give greater or lesser distortion, but the main features of the grid remain little changed.

Analysis on a σ_t-surface--The distribution of temperature, oxygen, and pressure on various surfaces of constant σ_t could then be drawn. For the purpose of studying the flow, temperature is the most satisfactory indicator on the σ_t-surface. (Chlorinity or salinity might equally well be used as each is a single valued function of temperature on a σ_t-surface. Here it is preferred to use chlorinity solely to determine density and thereafter, as its distribution is known in detail, to use temperature as the indicator.)

Oxygen-distribution on the σ_t-surface gives an independent indicator of the flow provided that the surface is not found at shallow depths where the oxygen is non-conservative.

The pressure-contours serve to locate the σ_t-surface but are non-conservative.

The temperature- and pressure-distribution on the surface $\sigma_t = 26.0$ are shown in Figures 3 and 4.

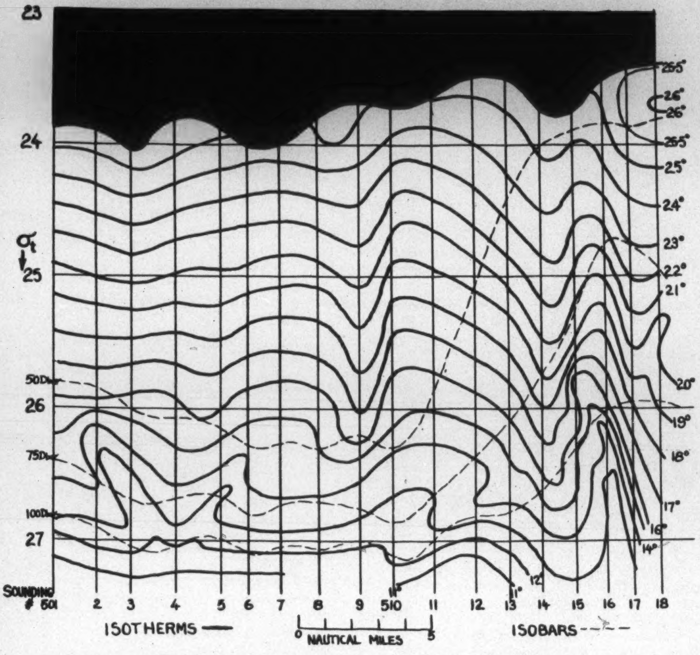


Fig. 6--Soundings on run perpendicular to Gulf Stream

Temperature-distribution on $\sigma_t = 26.0$--The distribution of temperature shows clearly the mutual intrusion of warm- and cold-water tongues (Fig. 3). The coldest parts of the cold-water tongues are found on the left and at the top of the grid while the warmest are at the right and bottom of the Figure; this suggests that the striated temperature is the result of cyclonic eddying motion and lateral shear. The "cold wall" of the Stream may be a statistical result of such eddy-like intrusions of cold slope-water.

The isobars on the surface as shown in Figure 4 show its configuration.

Oxygen-distribution--The distribution of oxygen is not shown here. Considerable doubt attaches to some of the oxygen-values which show great supersaturation. If, however, all supersaturated values are arbitrarily neglected as being the result of entrapped air in the sample-bottles or some such cause, the distribution of oxygen corresponds exactly to that of temperature--low oxygen in the warmer water and high values in the cold tongues.

This is brought out clearly in Figure 5 which shows the oxygen-temperature correlation for three different σ_t-surfaces. The linear correlation of temperature with oxygen for σ_t-constant shows that here only two distinct water-types are taking part in the mixing process and gives a definite picture of mixing in a σ_t-surface.

Cross-sections--The conventional sections which are used are not convenient for the study of water-types in a complex situation. In the foregoing study it was found that a cross-section employing σ_t as the vertical axis of ordinates was most suitable. Isotherms plotted on such a cross-section reveal at a glance the different water-types. (Lines of constant oxygen would also be suitable.) Isobars may also be entered on the cross-section to show the relation to the depth-scale and to indicate the stability.

A cross-section of this type is shown in Figure 6 for the soundings taken on a run perpendicular to the Stream (No. 518 is in the Stream). This run was made after the storm which broke the series at sounding No. 500 and can therefore not be located exactly relative to the previous soundings. The navigational data indicates, however, that it cuts across the region analyzed in Figures 3 and 4. A single water-type on this kind of cross-section would have isotherms parallel to the σ_t-lines whereas the boundary between different water-types is clearly shown where the isotherms are markedly inclined to the σ_t-lines. The cross-section supports the foregoing analyses.

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THE SUMMER-TIME VERTICAL HUMIDITY-GRADIENT OVER THE COLD WATER OF THE SAN JUAN ARCHIPELAGO

Phil E. Church

During the past three summers (1938, 1939, 1940) observations have been taken of the vertical humidity-gradient in the lowest meters above the sea-water at several locations near the Oceanographic Laboratories at Friday Harbor. Though the observations have not been continuous, owing to the instrumental equipment and the labor involved, the periods selected were typical of summer daytime-weather and the places from which data were obtained were representative of the condition prevalent above the water of the Archipelago.

Instrumental arrangement and observational procedure--Because of the contaminating effect on air-temperature of any size vessel and the lifting and crowding of air-layers flowing over the boat, the nearest approach to the optimum observation-condition is from a raft with as little freeboard as is consistent with safety (see Fig. 1). Accordingly, one was built of heavy logs and a mast stepped at one end. The freeboard was approximately 20 cm.

The instrumental equipment and arrangement was such that the temperature of the surface-water within two cm of the top (except when the surface was rough), wet- and dry-bulb temperatures at one, two, and four meters, and the wind-mileage at the same levels could be made. The anemometers were mounted on brackets extending outward from the mast in an undisturbed flow of air. The psychrometers were bracketed close to the mast. It was possible to keep the instruments held directly into the wind regardless of direction of tidal currents. At several stations the M. S. Catalyst was anchored within 100 meters of the raft. Observations of wind-mileage and wet- and dry-bulb temperatures were then obtained at a height of ten meters at the top of the foremast, the best place on board for exposure of the instruments.

Two Friez hand-aspirated psychrometers, fitted with special thermometers, were used at the four- and ten-meter levels when the Catalyst was available. The thermometers were graduated to 0°5 F with a scale open enough to permit accurate reading to 0°1 F. At the other levels, one and two meters, sling-psychrometers were mounted in a stationary position in a free exposure to the wind but shielded from both direct and reflected sunshine. When there was insufficient wind-velocity for good ventilation, artificial aspiration was maintained for these psychrometers. All thermometers were calibrated against a precision-thermometer and all readings have been corrected. When the raft was used alone the two hand-aspirated psychrometers were mounted at the two- and four-meter level.

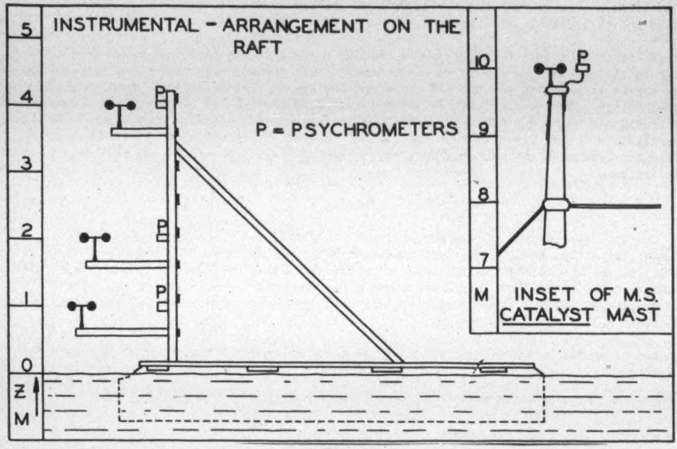

INSTRUMENTAL - ARRANGEMENT ON THE RAFT
P = PSYCHROMETERS
P
P
P
P
5
4
3
2
1
0
Z
M
10
9
8
7
M
INSET OF M.S. CATALYST MAST

Fig. 1

Three three-cup and one four-cup anemometers, all with registering dials, were employed. The divisions on the dials were to the 0.1 mile and, although readings to the 0.01 could be estimated easily, the instruments were read to the nearest 0.05 mile only. The calibration of the anemometers was relative to the four-cup, which was used as the standard, and corrections have been made accordingly.

Two, three, or four people read the instruments during the runs made. One person was assigned to the Catalyst. Two were usually assigned to the raft; one to read the instruments and the other to record the data. The instruments were read as nearly simultaneously as possible. On the raft a time-interval of one minute was necessary between readings at the one- and two-meter levels, and the four-meter level. This permitted time to make the readings at the lower levels and climb the mast. The one-minute interval between readings was rigorously maintained during most runs. Occasionally, it was possible to have only one person on the raft and then a two-minute interval was necessary to permit the observer to make the readings and record the data at one and two meters before climbing the mast to make the observation at four meters.

Observations were made at regular intervals of ten minutes in most cases. At each observation time, in addition to wet- and dry-bulb temperatures and wind-mileage at all levels, the surface-temperature, wind-direction, height of waves, and state of sky were also noted.

Surface-temperature of the San Juan Archipelago water--Except for a period of about two weeks in July, when warm water from the Straits of Georgia covers the surface in the channels between the islands, the water is cold all summer at most places [see 1 of "References" at end of paper]. The surface-temperature is remarkably homogeneous in the Strait of Juan de Fuca and the channels of the Archipelago; this averages about 10° to 12° C during July and August. Localities protected from rapid tidal currents are relatively warm, the surficial layer attaining 14° to 16° C as in East and West Sound, on Orcas Island.

Wind--The summer-time surface-wind is one controlled by the Pacific anti-cyclonic cell centered at about latitude 45° north which produces a northwest wind along the coast. When this air comes in contact with the cold water of the Inland Waters of western Washington a marked inversion, with its consequent stability, results. The topography then controls the direction of flow of the stable surface-layer.

The Strait of Juan de Fuca changes the wind-direction from northwest to west. Eastward from a line between Port Angeles and Race Rocks, the Strait opens up to a roughly circular shape with two sea-level outlets--the channels of the San Juan Archipelago to the northeast and Admiralty Inlet to the south. Daytime heating of the Puget Sound Lowland, which lies to the east of these water-areas, produces a marked diurnal variation in the wind-velocity. By mid-afternoon a sea breeze is set up between the air entering through the orifice of the Strait of Juan de Fuca and the heated surface of the Puget Sound Lowland. Eastward from Race Rocks, the air in the stable layer above the water spreads outward, entering the channels of the Archipelago as a southwest wind. The stability is sufficient to prevent much air from flowing over the islands; therefore, most of the air is concentrated within the channels where the velocity may reach as high as eight to ten meters per second by mid-afternoon. Most of the air within the channels has had a trajectory over cold water for approximately 80 miles or more.

Data--With due regard to safety, the raft has been towed to positions where the exposure would yield air that has had a long trajectory over water and where conditions are as typical as possible of the Inland Waters of Washington.

The data obtained from the raft and Catalyst have been reduced in the manner employed by Montgomery [2]. Data thus reduced show that the normal daytime condition over the cold water of San Juan Channel is one in which the vapor-pressure at four meters is greater than the vapor-pressure over the salt water, assuming saturation of the laminar boundary-layer. Invariably the vapor-pressure at ten meters has been greater than that at four meters.

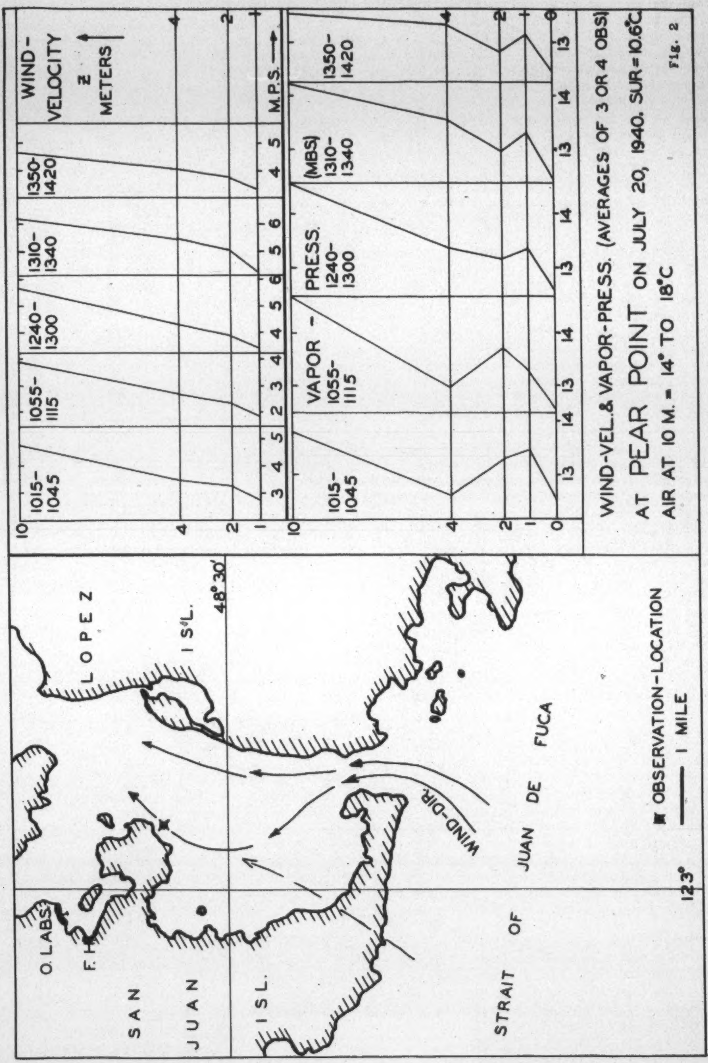
At Pear Point (see Fig. 2) on the east side of San Juan Island near the north end of Griffin Bay (an enlargement of San Juan Channel) observations were made on July 20, 1940. This location was chosen because air from the south to southwest had been over the water for a long distance. During the day the wind was from south-southwest to southwest and from velocity 3 to 5.5 meters per sec. The water-temperature remained constant at 10°6 C. With the lower wind-velocity in the morning the direction was more nearly south and had an inversion averaging about 3° C between the surface-water and the air at ten meters, but in the afternoon the velocity increased. Simultaneously, the inversion also increased, indicating that some air had been drawn across the lower end of the Island. Cirrus haze covered the sky. At no time did the waves exceed 15 cm in height. The wind-velocity and vapor-pressure for several periods of not more than 30 minutes' duration (four observations), when the wind was of nearly constant velocity, have been averaged and the data plotted in Figure 2. Using Witting's percentile lowering of the saturation vapor-pressure of sea-water, the air at one meter had a vapor-pressure consistently higher, by approximately one mb, than that of the laminar boundary-layer. A greater vapor-pressure was found at ten meters than at one meter, the difference amounting to slightly more than one mb. Though the vapor-pressure at four meters was less than that at ten meters, the former had a lower pressure than that at two meters when the wind-velocity was less than four meters per sec (at four meters). Similarly the vapor-pressure at four meters was less than that at one meter though slightly higher than that of the surface-water.

With wind-velocity of more than four meters per sec the vapor-pressures at these four heights assumed a straighter curve when plotted against height. Also vapor-pressure difference between the surface-water and ten meters decreased somewhat.

Wind-velocity was also plotted against height. In this case the values at two, four, and ten meters lay along a straight line when plotted on a linear scale. With light to moderate winds the velocity is a linear function of height, above two meters, when there is a marked increase of temperature (actual as well as potential) with height. The velocity at one meter was considerably less than that indicated by the slope of the line between two and ten meters. A discontinuity in wind-velocity was therefore indicated between one and two meters at the same height where there was a discontinuity in the vapor-pressure curve.

East Sound--The raft was towed to East Sound (Fig. 3) on August 16, 1940, when the Catalyst occupied a tidal-cycle station. Data were then obtained throughout a 23-hour period at ten-minute intervals except for a portion of the night.

East Sound, some eight miles long and a mile wide, lies in a nearly north-south direction with an abrupt high wall (up to 2,000 feet) on the east side. On the west side, the land is not much above 500 feet high. At the north end of East Sound the surface of Orcas Island separating the Sound from the water to the north is not higher than 20 feet. Wind, either northward or southward, is concentrated in this long narrow gap, open at both ends. At the time of the observations the wind was from the north with a fairly constant velocity of about eight to ten meters per sec except for five hours at night ($19^h\ 00^m$ to $1^h\ 00^m$). Though the wind had passed over a narrow neck of low land it was undoubtedly contaminated with air from the higher land to the west. Nevertheless, an inversion was present the whole 23-hour period.



WIND-VEL.& VAPOR-PRESS. (AVERAGES OF 3 OR 4 OBS)

AT PEAR POINT ON JULY 20, 1940. SUR=10.6°C

AIR AT 10 M. = 14° TO 18°C

Fig. 2

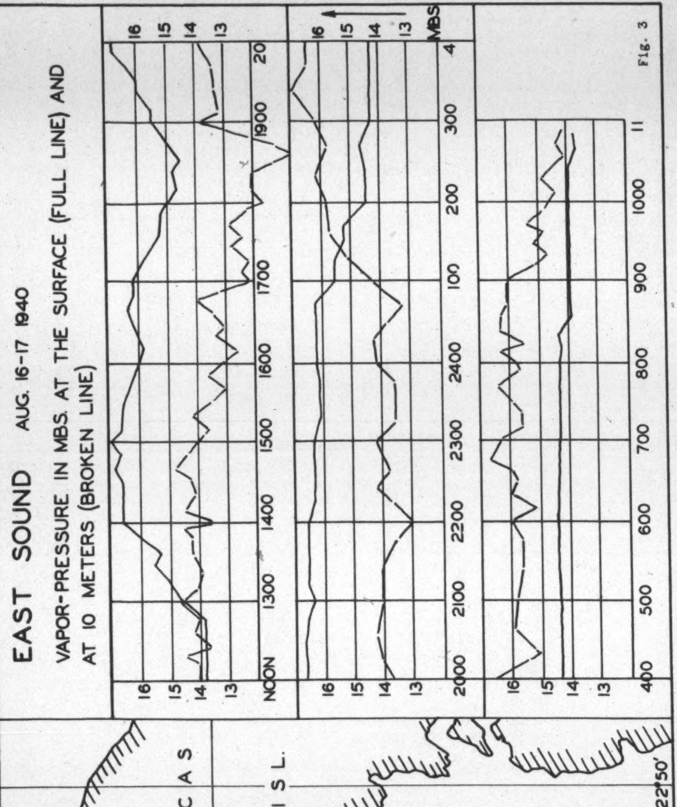

EAST SOUND AUG. 16-17 1940
VAPOR-PRESSURE IN MBS. AT THE SURFACE (FULL LINE) AND AT 10 METERS (BROKEN LINE)
16
15
14
13
NOON
1300
1400
1500
1600
1700
1900
20
2000
2100
2200
2300
2400
100
200
300
4
MBS
400
500
600
700
800
900
1000
11
ORCAS
ISL.
WIND
48°40'
122°50'

Fig. 3

Because of the enclosed nature of shallow East Sound, the surface-water was some 5° higher (15° C) than in the channels of the Archipelago.

The saturation vapor-pressures have been computed for the four levels in the air and for the surface-water, but only two levels have been graphed (see Fig. 3) to show the relation between the vapor-pressure at the surface and at ten meters. The vapor-pressures for one and two meters are questionable during all of the period except from $19^h\ 00^m$ to $1^h\ 00^m$ because the wave-height was from 20 to 40 cm. The raft was therefore awash most of the time. It is felt that the relationship of these two levels holds true for this one local area only.

From about noon until midnight the surface vapor-pressure was greater than that at ten meters. This is partly due to the high surface-temperature of the water during that phase of the tide. The vapor-pressure at the surface averaged about two mb more than at ten meters. The small change in temperature of the surface-water from one observation to the next resulted in a fairly regular line, which decreased sharply just after midnight. From noon until midnight there were marked fluctuations of the vapor-pressure of the air at ten meters. This doubtlessly meant considerable contamination of the marine air with that which had been over Orcas Island. During the calm period (from $19^h\ 00^m$to $1^h\ 00^m$) there was much less fluctuation in the vapor-pressure at ten meters. Artificial aspiration of the two stationary sling-psychrometers at one and two meters on the raft was maintained during this period.

At $1^h\ 00^m$ (August 17) the surface-temperature decreased, but the vapor-pressure at ten meters increased when the wind came up (approximately nine meters per sec). This steady velocity was maintained until the observations were completed. From $1^h\ 00^m$ until $11^h\ 00^m$ the vapor-pressure at ten meters was consistently above that of the surface-water. The difference averaged slightly more than one mb. Again the fluctuations in the vapor-pressure at ten meters were of such amplitude that it indicated eddies of air from Orcas Island.

Conclusions--From the observations made of the wind-velocity and vapor-pressures at one, two, four, and ten meters above the cold water of the San Juan Archipelago, it has been found that there exists, for light to moderate winds, an increase in wind-velocity which is a linear function of height above two meters when the air exhibits a marked inversion of temperature. This increase in velocity with height does not follow the well-established law that with no increase of potential temperature upward the wind-velocity is a function of the logarithm of height. Further, the vapor-pressure within the lower ten meters of the air over cold water shows a decrease downward to the surface. There is a marked discontinuity, however, between one and two meters which corresponds to the marked discontinuity at the same height in the wind-profile. Because of the decrease of vapor-pressure downward from ten meters, condensation is occurring at the surface. Therefore, the salt water would be reducing the moisture-content of the overlying air.

The height of the air from which the water is extracting moisture will, of course, be determined by the temperature-difference between the air and the surface-water and the length of time of the air over the water. No measurements have been possible above a height of ten meters, but at that height it has been demonstrated that the lid of the inversion has not been reached.

Further measurements of the vertical humidity-gradient are contemplated with more data to be obtained at closer height-intervals between the surface and two meters. It is also hoped that some method for obtaining wet- and dry-bulb temperatures above ten meters may be established.

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RESEARCH WITHIN PHYSICAL OCEANOGRAPHY AND SUBMARINE GEOLOGY AT THE SCRIPPS INSTITUTION OF OCEANOGRAPHY DURING APRIL 1940 TO APRIL 1941

H. U. Sverdrup and Staff

(Contributions from the Scripps Institution of Oceanography, New Series, No. 142)

Emphasis will again be placed on the activities within the fields of submarine geology and physical and chemical oceanography, although researches within the biological fields cover the greater part of the work at the Scripps Institution of Oceanography. The compilation and discussions of field-data and the studies in the laboratory have been greatly facilitated by assistance obtained from the Work Projects Administration Project No. 65-1-07-2317.

Last year's report concluded by mentioning that six cruises off the coast of southern California were in progress in cooperation with the United States Fish and Wildlife Service. The plans were carried out successfully in the period from March 5 to June 7, 1940. The cruises started out at an average interval of 16 days, each cruise lasting about ten days and 32 to 41 stations being occupied, depending upon conditions of weather. The results of the cruises clearly demonstrate the changes during spring and early summer when upwelling farther north becomes more and more intense and when the tongue of cold upwelled water at a distance of approximately 80 miles off the coast of southern California becomes more and more prominent. The earlier established relation between the distribution of diatoms and the character of the water was found to exist on most cruises, but some conspicuous discrepancies occurred indicating that the distribution of diatoms must also depend upon the existence of other organisms. The distribution of sardine-eggs which was examined in detail by members of the United States Fish and Wildlife Service showed a suggestive relationship to the character of the water-masses.

The network of stations was much closer on these cruises than on any previous cruise, the stations on a line being in general only 15 miles apart and the distance between station lines about 30 miles. In many instances stations were placed between the lines. In spite of this close network few localized eddies were found, but a streaky distribution of temperature and salinity prevailed with the streaks in the general direction of the currents. The currents are now being examined by R. B. Tibby who has developed methods for identifying a given water-mass such that the location can be ascertained from cruise to cruise. The area under examination was so small, however, that in most instances a water-mass could be traced from one cruise to the next only, having been carried out of the region by the time of the third cruise.

A similar program is in progress this season. Again six cruises are planned in cooperation with the United States Fish and Wildlife Service, but they will be spread over a greater length of time, the start of cruises being scheduled to take place at intervals of 24 days. Between the standard cruises which are expected to last ten to 12 days, special trips will be made for the purpose of examining in detail photosynthesis, problems in bacteriology, and the horizontal and vertical distribution of sardine-eggs and larvae. The first standard cruise was completed between March 21 and 30, 1941. It showed a distribution of temperature differing greatly in detail from that at the end of March, 1940, the difference being that in 1941 much warmer water was found close to the coast, probably due to the effect of numerous storms from the southwest. The picture was more similar to that of February, 1938, indicating that this year the winter conditions have prevailed longer than in earlier years from which comparable data are available.

Messrs. Fleming and Sverdrup have participated in the examination of the data from the cruises of 1940 and have furthermore been engaged in examination of the general distribution of plant-nutrients in all oceans and the general character of the water-masses and currents of the oceans. E. C. La Fond has conducted a considerable part of the routine computations related to the cruises and has continued the supervision of the studies of wave-heights and currents at the end of the Institution's pier and the measurements of sand-level along the pier and the adjoining beach. The latter investigations have attracted more and more attention because of the increasing interest in the protection and development of the beaches of southern California.

During the year Dr. L. Lek has worked at the Institution on problems in physical oceanography and has particularly studied the water-transport by a number of the larger currents of the oceans. Dr. H. R. Seiwell of the Woods Hole Oceanographic Institution has been a visitor since November, 1940, and has worked up a number of his observations on internal waves.

In July and August, 1940, Dr. R. T. Young, Jr., of Worcester Polytechnic Institute, completed an apparatus for measuring in the laboratory the absorption of light in samples of distilled water or of sea-water. Unfortunately, because the E. W. Scripps was having a new main engine installed, no provision could be made for obtaining samples of sea-water from any distance from the coast. A few samples were obtained by use of a motor-boat. The unfiltered samples showed a marked but irregular decrease in the transparency of the surface-water on a distance of 13 miles from the coast, and at two stations an irregular variation with depth was found. Filtration increased with the transparency of samples from 60 to 70 per cent of that of pure distilled water up to 90 to 95 per cent. Young concluded that most of the observed variation in transparency was due to suspended material which could be removed by a filter. It is hoped to continue the observations and, particularly, to find methods by which the relative variations in transparency which can be measured directly at any station may be converted into absolute values.

At about 40 stations occupied on each of the six cruises made by the E. W. Scripps during the first half of 1940, serial phosphate determinations to depths of about 500 meters were made by E. G. Moberg and J. Lyman. The results have been prepared for publication and later will be correlated with the dynamical, physico-chemical, and biological conditions in the area investigated. A preliminary examination shows a marked relation between phosphate-content and the current-systems and water-masses. Because phosphate can be determined rapidly and on board ship, there is a good possibility that it can be used as an indicator of the origin and movements of water-masses.

A study has been begun by E. G. Moberg of the results of several thousand calcium-determinations made on serial water-samples from several regions in the Northeastern Pacific from the Aleutian Islands to Panama, including several hundred samples from the Gulf of California. From previous investigations here and elsewhere it has been concluded that in normal sea-water the ratio (Ca:Cl) is constant, but a preliminary study of the large body of data now available indicates an increase in the ratio with increasing salinity. It has not yet been definitely established whether this is true also at the surface. According to what is known of the solubility-relations of calcium salts in sea-water, the opposite would be expected.

John Lyman has concluded an investigation extending over several years of the buffer-mechanism of sea-water. The complete solution of the problem for natural sea-water requires knowledge of the magnitude of two dissociation-constants of carbonic acid and two of boric acid, as well as their respective variation with temperature and chlorinity. In the past such measurements have been made separately to evaluate single constants, but use of the glass electrode for determination of hydrogen-ion concentrations without disturbing the sample under study makes it possible to obtain continuous and highly accurate titration-curves of normal and carbon dioxide-free sea-water, from which the four dissociation-constants can be calculated simultaneously. The results obtained will find application in analyzing a number of geological and biochemical processes taking place in the sea and on the sea-bottom.

A few years ago a study of methods for determining iodine in sea-water was begun, and an adaptation of one method was found to give reliable results, showing that in this locality the content of iodine is in the order of 0.05 milligram per liter. During last summer additional studies of the iodine-content and of methods for its determination were made by Dr. W. L. Burdick of Sacramento Junior College. From serial water-samples from depths to 800 meters it was found that, unlike the common plant-nutrients, the concentration of iodine is approximately constant at all depths.

G. F. McEwen reports that in addition to the usual work on advance indications of air- and sea-temperatures and seasonal precipitation in Pacific coastal areas, a special study of the Colorado River runoff was begun. This project, carried on through a cooperative arrangement with the Bureau of Power and Light of the Department of Water and Power of the City of Los Angles, has for its ultimate objective an understanding of the behavior of the seasonal runoff of the Colorado River, in relation to precipitation in the drainage-basins, that will lead to general forecasts of the runoff for periods of several years.

From the base-maps of the drainage-areas and location of weather-stations, studies are being made of the correlation between the relatively short and somewhat fragmentary records made within these areas and the long continuous records at appropriate central United States Weather Bureau stations. These investigations are intended to provide a convenient means of estimating the precipitation over any desired portion of the area.

One method of using such data for forecasting runoff is based upon the assumption of a regular and continuous replenishment of a stored supply of water to the atmosphere combined with its dispersion, partly in accordance with a random series of rare events. Another method assumes the time series to represent numbers of certain rare events which occur in respective time-intervals (at random, with certain probabilities) and repeat themselves after certain periods of time.

A special study has been continued by Dr. Gorczynski with the help of McEwen concerning aridity-percentages. These results have been represented on a large number of maps involving the world as a whole and on larger-scale maps of California and adjacent regions. The aridity-percentage equals (latitude-factor) x (precipitation-ratio) x (temperature-range). The latitude-factor equals the cosecant of the geographical latitude times a factor that limits the aridity-percentage to 100 per cent for the most arid region of the Sahara Desert. The precipitation-ratio equals (maximum minus minimum annual precipitation) divided by the average for the interval. Problems of reducing this ratio to a standard (50-year) interval and of making the proper corrections when the three highest and three lowest values of the annual precipitation are used have been investigated by McEwen. He has nearly completed an extensive investigation of such statistical problems, including the standard errors of the precipitation-ratio. Convenient tables and diagrams prepared for the application of these results were used in the computations for the Gorczynski maps. McEwen's investigations led R. D. Gordon to make supplementary studies, not yet completed, of the correlation of simultaneous errors involved in two different estimates of the same quantity.

Beginning with very general assumptions concerning (turbulent) mixing processes in a fluid, Gordon has begun an application of the invariant-integral theory of Edouard Goursat which promises to give significant results in connection with such problems as the determination of "virtual diffusion-coefficients" in the ocean, or the study of production- and consumption-processes in situ (without knowledge of the magnitudes of diffusion-coefficients). The study begins with a linear partial differential equation (or form) known to be elliptic, but with unknown second-order coefficients, and one or more particular solutions are supposed known presenting, for example, concentrations of salt, oxygen, or temperature.

Daily observations of sea-surface temperature and daily collected water-samples have been obtained from five localities on the California Coast, exclusive of those taken at the Scripps Institution Pier. The salinities of the samples have been determined by the specific-gravity method. Other observations of surface-temperatures have been obtained from the U. S. Lightship tenders Sequoia and Lupine, and from tuna boats. The cooperation of organizations and personnel is greatly appreciated.

Conferences have been held with Dr. O. E. Sette for the purpose of arriving at suitable statistical methods of dealing with practical problems as they arise in his investigations of the sardine-problem. Some assistance likewise has been given to local biologists in connection with their mathematical and statistical problems.

The sediments division of the Scripps Institution, in charge of R. Revelle, has been occupied principally in carrying out routine mechanical and chemical analyses on the large numbers of bottom-samples collected in the Gulf of California and in the southern California region in recent years. Studies of the sulphur-cycle in marine sediments have been continued and formed one of the major problems investigated on the expedition of 1940 to the Gulf of California. Long cores of green mud from this area frequently stink of hydrogen sulphide from top to bottom and it is found, indeed, that near the bottom of many cores all the sulphate in the interstitial water has been reduced to sulphide. No iron sulphide is present, however, suggesting that through diagenetic processes the iron present in the sediment has been locked up in a compound less soluble than iron sulphide.

M. L. Natland continued his work on the foraminiferal remains present in the bottom-deposits in the collections of the Scripps Institution. A study of 400 species of foraminifera in 170 samples collected by the United States Navy and the United States Coast and Geodetic Survey in the Panama Area has now been completed and it is possible to assay the relative effects of different ecologic factors by comparison of the faunas found in these tropical waters with those found off southern California.

During the summer and fall of 1940, F. P. Shepard completed his reports to the Geological Society of America on field-work conducted mainly in 1938. He continued his observations on shore-lines, repeated numerous soundings in the La Jolla Canyon, and collected a great amount of data on rip-tides and rip-currents for a paper which was submitted to the Geological Society of America.

On the E. W. Scripps cruise to the Gulf of California in 1939 it was found that in this region at the present time are reproduced many of the conditions which characterized certain land-areas of great geologic interest in the past. Accordingly, a second expedition under the joint sponsorship of the Geological Society of America and the Scripps Institution was organized, and the three months of October, November, and December, 1940, were spent in Lower Californian waters. This expedition had a single general purpose, namely, to study the geologic processes which are or have been active in the Gulf of California through a coordinated investigation of the recent geologic history of the land, of the bottom-topography and sediments, and of the nature of the marine environment. The geological and oceanographical work carried out at sea was under the joint supervision of Roger Revelle and Francis P. Shepard. Sydney Rittenberg was in charge of the chemical and bacteriological studies made on the Gulf waters and on sediment-samples collected from the sea-bottom, while Kenneth Emery and Robert Dietz assisted in all the operations at sea and were particularly responsible for the taking of cores and other samples of bottom-sediments. The geology and paleontology of the island and land areas in and surrounding the Gulf were studied by Charles A. Anderson and J. Wyatt Durham.

From the geologic work on shore it is possible to conclude that the Gulf of California existed in essentially its present form before late Pliocene time. Considerable tectonic activity has taken place since the Pliocene, however, and has probably been responsible for the formation or modification of many of the deep troughs and basins of the Gulf floor, as well as for the present outlines of the islands and surrounding coasts.

During the course of the expedition the fathometer echo-sounding machine was run almost continuously whenever the vessel was under way. Records of about 25,000 soundings were obtained, greatly amplifying the results of the cruise of 1939 and establishing many features of the submarine topography in a region where previous depth-measurements were almost lacking. Special studies were made of supposed submarine fault-scarps and fault-troughs, of submarine canyons, and of submarine terraces. The Gulf of California appears to be essentially a broad fault-trough, roughly V-shaped in cross-section, within which a series of narrow basins have been formed by faulting subsequent to that which gave rise to the Gulf as a whole. Deep terraces observed along the sides of the Gulf can be explained in part as remnants of the old floor prior to the development of the inner troughs. The recency of tectonic movement is indicated by the absence or narrowness of the continental shelf in many places and by the relative scarcity of canyons cut into the submarine slopes.

Approximately 100 cores and 120 large-snapper samples of bottom-sediments were taken. One of the outstanding results of this work was the collecting of cores considerably longer than any previously taken in the deep waters of the open sea. Several cores over 15 feet long were recovered and one was nearly 17 feet in length. These great lengths were in part due to the relatively soft character of some of the bottom-muds and in part to the ingenuity of Emery and Dietz who devised several important improvements in the coring apparatus. Core-barrels 20 feet long and 2-1/2 inches in diameter were employed, and these were equipped with liners and core-catchers of thin flexible celluloid instead of the metal or glass formerly used.

The floor of the Gulf of California is unique so far as the present sea-bottom is concerned, in that over many thousands of square miles it is covered with a green, finely laminated, highly organic diatomaceous mud which is apparently the modern analogue of the Miocene diatomaceous shales in the California coast ranges. On drying a core of this diatomaceous mud the laminations are clearly seen as alternating white and green bands about 0.2 to 1.0 mm thick, which become more closely spaced as the bottom of the core is approached, probably owing to compaction. If the laminations represent annual layers corresponding to seasonal fluctuations in the production of plankton-diatoms in the overlying waters, the rate of deposition of these relatively loose muds may be calculated as about one foot in 350 years.

The seasonal character of phytoplankton-production in the Gulf of California is abundantly demonstrated by observations made on the two E. W. Scripps expeditions. On the cruise of 1939 which took place in February and March, the waters over large areas were reddened and opaque, so great was the phytoplankton-population. When the expedition of 1940 first reached the Gulf, the surface-waters were warm, blue and clear, the phytoplankton-population and the content of nutrient salts were very small, and interchange with nutrient-rich deep waters was prevented by the stable density-stratification accompanying the high temperatures of the surface-waters. With the development of northwesterly winds of gale force, which began in November, repeated measurements of the vertical distribution of temperature, salinity, oxygen, phosphate, and silica showed that the warm surface-waters were being blown southward while upwelling of cold water of low-oxygen and high-nutrient-salt content, and mixing of surface and subsurface waters were taking place. At the same time quantitative samples showed a marked increase in phytoplankton-population and small patches of red water were seen in December.

That the diatom-frustules produced in the winter and spring months quickly settle through the water was evidenced by repeated measurements of the amount of remains of diatoms in the water at depths of 1,000 meters or more. In October, when the surface-waters were bare of phytoplankton, practically no remains of diatoms were found in the deep water; after plankton-production had proceeded for a few weeks near the surface, it was possible to collect many thousands of diatom-frustules per liter even at depths greater than 1,000 meters.

Large-scale phytoplankton-production and huge diatom-populations occur elsewhere, yet the bottom-deposits off the American west coast, for example, are not notably diatomaceous because the frustules settling into deep water become dispersed and dissolve before reaching the bottom. In the last analysis, the rate of silica deposition on the bottom must be exactly equal to the excess of silica brought into any region over that carried out of it by water-movements. From this point of view, the formation of siliceous deposits on the floor of the Gulf must be due essentially to the character of the circulation and the presence of these deposits can be taken as evidence that silica-rich water flows into the Gulf at depth and that silica-poor water leaves it at the surface. This is confirmed by the observed increase in concentration of silica in the deep water from the mouth of the Gulf to the region west of Guaymas and by the fact that the deep waters of the Gulf have about 30 per cent more silica per unit of volume than do those of the open sea.

The mechanism of silica deposition has been discussed at considerable length because it beautifully illustrates the unity and interrelationships of the sciences of the sea. Several other kinds of investigation of geological processes in the water and on the bottom were carried out on the expedition. These included current-measurements from the vessel anchored in depths of 1,000 to 2,000 meters, measurements of the amounts of decomposable organic matter in the water and on the bottom, of the vertical distribution of bacteria in cores and in the water-column, determinations of pH, sulphide and sulphate content. Subsequent studies comprised the distribution of organic pigments by Dr. D. L. Fox and L. J. Anderson, and examination of gaseous hydrocarbons by Dr. B. Washburn of the United Geophysical Company of Pasadena. Because of the great length of the cores collected, the variety of sediments encountered, and the high organic-matter content of some of the muds, the Gulf of California represents an excellent field-laboratory for the study of diagenesis.

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SUMMARY OF SOME RESULTS OF INTERNAL-WAVE INVESTIGATIONS IN THE NORTH ATLANTIC

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(Contribution No. 276, Woods Hole Oceanographic Institution)

Observations at 13 anchor-stations occupied by *Atlantis* within recent years have substantiated Helland-Hanson's earlier suggestion that short-period vertical oscillations of the water-layers cause significant time-variations of oceanographic properties throughout the ocean space. And, hence, occasional vertical series of oceanographic observations may not necessarily represent average conditions at the locality sampled.

Measurements of vertical oscillations of the water-layers of the deep ocean were obtained from temperature- and salinity-samplings, repeated as rapidly as possible over periods ranging from 27 to more than 300 hours, at 17 levels, between surface and 1,200 to 1,300 meters. Since the localities selected for study were characterized by gently sloping isopycnal surfaces, the corrected observations when plotted as time-series clearly show the vertical displacements.

A recent analysis of conditions at an *Atlantis* station in the southern North Atlantic (Station 3245 in 25° 32' north and 53° 45' west) comprised materials from 28 repeated samplings of the water-column at 17 levels between surface and 1,100 meters, obtained during an approximate 26-hour period (02^h 54^m GMT, January 23, to 04^h 45^m January 24, 1939) while the vessel was anchored at a depth of 5,000 meters. During this time temperature at standard depths ranged from 0°.32 to 2°.25 because of vertical displacements of the water-particles. The smaller variations (0°.32 to 0°.36) occurred where the water-column was least thermally stratified and where vertical displacements were largest (48 to 56 meters), whereas larger variations (1°.31 to 2°.25) occurred at depths characterized by an increased vertical temperature- (and density-) stratification. Relationships between vertical density- and temperature-distributions, vertical displace-

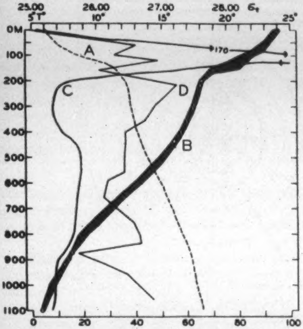

Fig. 1--*Atlantis* Station 3245: 02^h 54^m, January 23 to 04^h 45^m, January 24, 1939 (GMT) [A = average vertical distribution of density (σ_t); B = average vertical distribution of temperature, variation at fixed depths indicated by width of ribbon; C = average vertical rate of change of density per meter, $\Delta\sigma_t/\Delta Z$; D = vertical displacements of water-column during observation-period (referred to bottom scale, meters)]

ments and temperature-variations, and vertical rate of change of density at Station 3245 are illustrated by Figure 1.

Analytical transformation of the observational materials by harmonic analysis of vertical displacements of 22 selected isotherms (23° to 6°), and subsequent statistical treatment, revealed that for the observation-period the oscillations could be suitably represented by combinations of two sine-waves having periods of 12 and 24 lunar hours. The coefficients, tabulated in Table 1, have had phases adjusted to refer from 13^h $32^m.3$, January 22, 1939 (GMT), the time of the Moon's upper transit at the Greenwich meridian, but are not to be construed as being valid outside the observation-period. Adequacy of the empirical representation is manifested by the residues, resulting after subtraction of the two sine-waves from observed displacements, forming a random distribution.

Within the water-column, vertical variations of phases, amplitudes, and ratios of amplitudes are identified with its structure (Fig. 1, Table 1). In the upper strongly stratified layers, between approximately 50 and 150 meters, phases changed rapidly with depth and amplitudes were relatively small with the semidiurnal dominating. Somewhat deeper, in less-stratified water, as between 150 and 450 meters, phases were more uniform and amplitudes attained maximum values with the semidiurnal again dominating. In still deeper water of increased stability, as between 550 and 1,050 meters, vertical variations of phase-angles increased, amplitudes in general decreased, and the diurnal wave usually dominated. For 19 of the 22 vertical displacements studied, semidiurnal and diurnal maxima occurred within three hours of each other, and for 14 of the 22 cases semidiurnal amplitudes were greater (Table 1); dominance being particularly striking in depths less than 700 meters. Throughout the water-column (to 1,050 meters' depth) the range of amplitude-ratios [(semidiurnal/diurnal) = 8.00 to 0.185] was approximately the same as the range of ratios computed from tidal harmonic constants at shallow-water tidal stations encircling

Table 1

Isotherm	C_0	C_{24}	α_{24}	C_{12}	α_{12}	(C_{24}/C_{12})
23.0	62.52	5.39	23.39^h	5.56	7.08^h	0.97
22.0	99.28	4.56	22.56^h	5.09	7.71^h	0.90
21.0	118.74	0.84	7.50^h	6.72	8.45^h	0.125
20.0	135.11	0.94	11.20^h	2.04	8.96^h	0.461
19.0	157.58	2.48	12.07^h	2.53	1.01^h	0.980
18.0	216.46	13.33	15.73^h	11.01	3.36^h	1.211
17.5	295.80	5.41	15.86^h	10.27	2.66^h	0.527
17.0	356.79	2.85	17.89^h	11.21	3.15^h	0.254
16.5	400.76	2.43	15.23^h	8.52	3.75^h	0.285
16.0	434.22	4.42	13.17^h	15.34	3.58^h	0.288
15.0	497.08	4.01	13.53^h	12.82	2.65^h	0.313
14.0	555.24	1.57	16.00^h	11.82	2.43^h	0.133
13.0	607.66	1.03	2.12^h	5.78	3.72^h	0.178
12.0	653.18	3.87	17.65^h	2.76	4.29^h	1.40
11.0	702.23	4.69	17.60^h	5.12	5.48^h	0.916
10.0	755.36	8.28	7.00^h	4.22	4.85^h	1.962
9.0	805.28	6.88	11.46^h	5.02	3.97^h	1.371
8.5	835.32	7.82	14.53^h	3.33	4.92^h	2.348
8.0	875.05	2.79	21.44^h	1.21	2.58^h	2.306
7.5	918.95	6.54	0.76^h	1.21	3.64^h	5.405
7.0	956.95	4.24	21.03^h	9.36	11.16^h	0.453
6.0	1057.45	11.87	22.58^h	8.24	11.53^h	1.44

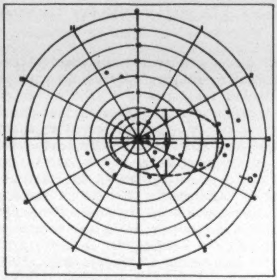

Fig. 2--Harmonic dial for 12-lunar-hour sine-waves in vertical displacements of 22 isotherms at *Atlantis* Station 3245

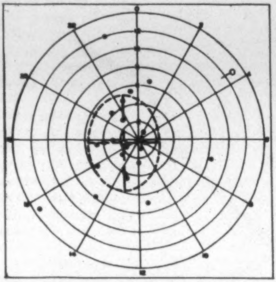

Fig. 3--Harmonic dial for 24-lunar-hour sine-waves in vertical displacements of 22 isotherms at *Atlantis* Station 3245

[Scale refers from Moon's upper transit at Greenwich (13^h 32^m, January 22, 1939), and inner 0 indicates Moon's upper transit at meridian of Station 3245 (17^h 14^m, January 22, 1939, GMT); each dot marks an isotherm, length of vector from center gives amplitude (in meters) and its direction, the phase in lunar hours]

Station 3245 (6.414 at Tybee Island Light in 32° 02' north and 80° 51' west and 0.252 at St. Thomas Island in 18° 20' north and 64° 56' west).

Statistical analyses of the coefficients of the two sine-waves were undertaken to obtain information concerning space-variability and average properties of the oscillations. Methods similar to those developed by Bartels for time-series analysis of other geophysical data were employed. In Figures 2 and 3, coefficients of the lunar diurnal and semidiurnal waves for the 22 isotherms (Table 1) are plotted in polar coordinates; each coefficient is represented by a single dot, its amplitude being given by distance from the center of the dial and its phase by direction. The mass-centers of the two groups of points represent properties of the average sine-waves, and the 50 per cent "probability-ellipses" were computed as suitable expressions for the scatterings. Geometric properties of the two groups of points as indicated by ellipticity, rotation of the ellipse, relative scattering, relative variability in distribution of amplitude and phase, etc., as well as average properties of the two frequencies, furnish a basis for comparison of conditions observed at various localities. The statistical constants involved may always be computed and are representative of the Gaussian distributions best fitting the groups of points. The results are treated with that proverbial "grain of salt" necessary in all applications of probability-theory.

Distinctions in geometric properties of lunar diurnal and semidiurnal groups of points are illustrated by the ellipse constants tabulated in Table 2. In this Table values under the heading "isotherms" were computed from harmonic constants derived from vertical oscillations of 22 isotherms (Table 1) whereas those under the heading "standard depths" were derived from phase- and amplitude-relations at forty-three 25-meter intervals between surface and 1,050 meters. Both sets of values are essentially the same, and reality of the average properties has been statistically demonstrated.

Table 2

Item	Isotherms		Standard depths	
	12^h	24^h	12^h	24^h
Major axis, P_1	7.0643	5.2591	6.8339	5.1528
Minor axis, P_2	4.2053	3.8749	4.1272	3.5638
Ratio (P_1/P_2)	1.6799	1.3572	1.6558	1.4459
Direction P_1	3^h	12^h	3^h	12^h
Dispersion	6.983	5.548	6.781	5.321
Average vector: Length	.....	.....	4.38	2.21
Phase	.....	.....	$2\overset{h}{.}97$	$17\overset{h}{.}17$

Both groups of points possessed marked ellipticities indicating that the small average amplitudes (Table 2) resulted from combination of larger amplitudes but of nearly opposite phase. The semidiurnal coefficients had the most marked ellipticity, largest average amplitudes, and greatest amounts of scattering. Directions of the major axes of the ellipses differed by 90°, being 03^h for the semidiurnal, 12^h for the di-

Table 3

Item	Lunar semidiurnal	Lunar diurnal
Major axis, P_1	10.8233	1.9732
Minor axis, P_2	3.0022	0.9583
Ellipticity (P_1/P_2)	3.6051	2.059
Direction P_1	$2^{h}.3$	$12^{h}.0$
Dispersion	9.534	1.860
Average vector: Length	2.604	1.380

urnal, and that for the semidiurnal cloud nearly coincided with the phase of its average vector as compared with a five-hour difference for the diurnal cloud.

Positions of the axes of the ellipse indicate greater variability for phase-angles than amplitudes (Figs. 2 and 3). For the 12-hour point aggregate the major axis end-points corresponded to amplitudes of 3.6 and 10.7 meters and to phase-angles of 93° and 261°, and the minor axis end-points to 5.1 and 5.9 meters and to phase-angles of 44° and 143°. For the 24-hour point aggregate the major axis end-points corresponded to amplitudes of 5.2 and 5.8 meters and to phase-angles of 196° and 342°, and the minor axis end-points to 2.4 and 5.6 meters and to 98° and 267°.

Certain consequences of the analysis are brought out by consideration of results of a similar treatment of theoretical vertical displacements at Station 3245 as computed according to Fjeldstad's internal-wave theory. The possible internal waves (relative values only) corresponding to a given, continuously varying density-distribution (as at Station 3245) may theoretically be computed by numerical integration of a second-order differential equation, and although an infinite number of solutions, corresponding to an infinite number of internal waves, are possible, practical consideration limits computations to the first four. Absolute theoretical values, obtained by a least-square fitting of the combined relative displacements to observed phases and amplitudes, were subjected to the same statistical treatment as the observed values. The results suggest that, regardless of irregular influences, good representation of observed conditions is obtained from the theoretical internal-wave considerations of Fjeldstad. Statistical distinctions between diurnal and semidiurnal point aggregates are concordant with those existing between the two groups of coefficients computed directly from observations (Tables 2 and 3). Thus the major axis, P_1, the ellipticity, (P_1/P_2), the average vector, and the dispersion of the theoretical semidiurnal point aggregate exceed similar characteristics of the diurnal. Likewise, the major axis of the theoretical diurnal ellipse is, like the observed, in a direction clockwise from that of the semidiurnal ellipse--possible values being 2.32 hours for the semidiurnal and 12 hours for the diurnal.

Comparison of properties of theoretical and observed semidiurnal coefficients shows, as the most striking feature, an increased ellipticity of the former from (P_1/P_2) = 1.68 to (P_1/P_2) = 3.61 (major axis increased 53 per cent and minor axis diminished 29 per cent), illustrating that theoretical semidiurnal wave-motions of the water-column would be of more nearly opposite phases. The absolute scattering of the points increased from 6.983 to 9.534 for the theoretical aggregate and the major-axis direction of the theoretical ellipse with a possible value of 2.32 hours is not greatly different from the 3-hour value computed for the observed coefficients.

Comparison of the two groups of diurnal coefficients reveals ellipticity of the theoretical values increased from (P_1/P_2) = 1.36 to (P_1/P_2) = 2.06. The absolute scattering of the points diminished from 5.55 for the observed to 1.86 for the theoretical group and rotations of both ellipses appear identical, directions of both major axes being 12 hours.

Consideration of phases and amplitudes of the average sine-waves characterizing the observed vertical oscillations of the water-layers between surface and 1,050 meters suggest the possibility of a connection between internal-wave and tidal mechanisms. These average properties, demonstrated to be statistically significant, as given by Table 2, show a phase-difference (diurnal minus semidiurnal) of 2.2 lunar hours and an amplitude-ratio (semidiurnal/diurnal) of 1.98. The former is not greatly different from the phase-difference of approximately 3.5 hours between semidiurnal and diurnal tides at the geographical position of Station 3245 (as given by the cotidal charts of R. Sterneck) and the latter lies within the range of ratios of semidiurnal to diurnal amplitudes of 2.98 to 0.25 computed from tidal harmonic constants for the not too distant West Indian Waters.

Since tidal observations have been entirely restricted to the comparatively shallow portions of the sea, actual conditions in the deep waters are unknown. Consequently, endeavors to link up tidal and internal-wave mechanisms need be dealt with cautiously. However, in view of the general support given to this conception by the present, as well as other methodical investigations, there is strong indication of relationship between tidal and internal-wave mechanisms, although, as pointed out by Helland-Hansen years ago, the question of how the tidal wave can produce vertical movements of the dimensions observed in the different strata of the sea is at present inexplicable.

Table 4

Internal-wave order	Propagation velocities, cm sec^{-1}		
	Station 3245	Station 3091	Station M.S. - 68
1	259	276	267
2	110	87	90
3	80	70	75
4	54	50	49

Propagation-velocities of the first four internal waves at Station 3245, as computed from Fjeldstad's equation, range from 259 to 54 cm/sec, the velocity-diminution with increasing order being an approximate harmonic progression. These values agree fairly well with similar results from two widely separated locations in the North Atlantic of approximately the same depth (about 5,000 meters); one computation having been made by Fjeldstad (Michael Sars 68) at a position 39° north in 51° west, and the other by this writer for a station (Atlantis 3091) about 110 miles northwest of Bermuda (Table 4). As a tentative result, fair approximation to the propagation-velocities, C_n, of the internal waves in the open ocean is given by

$$C_n \text{ in (cm/sec)} = 221/N$$

N being the order of the wave. Discrepancies in this empirical representation chiefly affect the first two orders; from information at hand, differences for higher orders appear irrevelant. Reduction in propagation-velocities occurs in the less deep waters; for a station of 580 meters' depth in the Faero Shetland Channel (Michael Sars 115) approximation to propagation-velocities of the internal waves given by Fjeldstad is

$$C_n \text{ in (cm/sec)} = 78/N$$

The length of the first-order internal wave characterizing the open Atlantic may be taken as approximately 100 km, or about 1/100 the length of the semidiurnal tidal wave at the mean depth of the oceans. Likewise, the ratio of length of the first-order internal wave to the mean depth of the oceans is of the order of magnitude of 10^{-2} whereas that for the semidiurnal tidal wave is 10^{-4}.

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AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30—MAY 3, 1941

SECTION OF VOLCANOLOGY

REPORTS AND PAPERS

WASHINGTON, D.C.
APRIL 30, 1941

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REPORTS AND PAPERS, SECTION OF VOLCANOLOGY
UNITED STATES DEPARTMENTAL AUDITORIUM
9:00 A.M. AND 2:00 P.M., APRIL 30, 1941

HELIUM RETENTIVITIES OF MINERALS

N. B. Keevil

The retentive properties for helium of various minerals are of both mineralogical and geological importance. Since the degree of retention of helium is generally appreciable and helium is present in different concentrations in different rock-minerals, the rate of migration of helium through minerals must be extremely slow, even with respect to geological time. An excellent mechanism is thus available for studying the effects of geological processes upon the internal structures of minerals.

During the past two years about 80 mineral-samples have been studied in the writer's laboratory in order to find the variations in helium retentivity with divers crystal structures and with changes in geological environment.

While the study of mineralogical features has been of interest, it has been the primary purpose of this investigation to gather sufficient data to form a basis for calculating helium ages from experimental determinations of helium indices [see 1 and 2 of "References" at end of paper].

The need of such data has been made obvious by the discrepancies which appear when the results of several hundred helium-index determinations of rocks are compared with the sequence of their geological age. On the whole, the agreement has been good when similar type rocks have been compared [3, 4, 5], but some spurious results have required explanation. Two extreme examples are the values of five million years for a well-dated Ordovician lava, and eight billion years for a pre-Cambrian carbonate. While these results can be explained by the loss of helium from a glassy rock and by the inclusion of magmatic helium in a vein-mineral, respectively, lesser discrepancies are less readily explained and may not be detected at all. It seems safe to assume on the basis of our experience that contamination by magmatic helium is not common so the primary problem is that of helium retentivity.

An obvious simplification has been to compare material of similar composition and texture [4], or to concentrate on one particular mineral. Hurley and Goodman [6] have claimed magnetite to be a suitable mineral for which they have given a tentative time-scale. However, if it becomes necessary to work on one mineral alone, the method will be of little more use than the lead-method applied to radioactive minerals. Furthermore, there is evidence that magnetite may lose more than half of its radiogenic helium, so that other factors than mineral type must be taken into consideration. If these factors could be evaluated for common rock-minerals, it would be a tremendous step forward in that the helium-age method could be applied to materials commonly encountered in geological work.

In this broader problem, too few results have been obtained to warrant drawing conclusions, but enough data have accumulated to render helium-age determinations a little more useful in geological work than they were a year or so ago.

Table 1--Retention of helium in minerals

Mineral	Retentive factor	
	Range	Average value[a]
Pyroxene	0.2 - 2.2	0.6
Hornblende	0.2 - 3.8	0.6
Biotite	0.2 - 1.2	0.5
Magnetite	0.2 - 12	0.5
Garnet	0.2 - 2.7	0.65
Ferric concentrates	0.04 - 1.8	0.25
Quartz	0.04 - 1.2	0.25
Feldspar	0.02 - 0.5	0.2
Rare minerals	0.03 - 25	0.35

[a] Values greater than 1.1 excluded.

The results of helium-retention studies are summarized in Table 1. The retentivities were calculated from experimental helium-index values, and helium ages based upon geological data.

It will be noted that there is a considerable variation in the retentive properties from mineral to mineral, and even for one kind of mineral from one rock to another. The variation between different minerals seems to be related to structure in a general way, the closer-packed oxide and ferromagnesian-silicate structures showing higher retentive properties than the more open structures of quartz and feldspar. Structure-type alone, however, is not the determining factor because biotite shows a high degree of retention and the results are so variable.

Table 2--Evidence for magmatic helium in carbonates

Sample	Location	Apparent retentive factor
Fluorescent calcite	Franklin, N.J.	0.3
Non fluorescent calcite	Franklin, N.J.	1.0
Calcite	Franklin, N.J.	6
Calcite	Franklin, N.J.	6
Fluorescent calcite	Franklin, N.J.	14
Basic dyke with carbonate	Red Lake, Ontario	4.5

Theoretical calculations [7] have indicated that no diffusion would be expected through regular crystalline structures of most common rock-minerals, although some of the spacings were shown to be near the border-line for self-diffusion of helium. These calculations were based upon idealized crystal structures derived from X-ray data, but allowances for the effects of known types of crystal imperfections indicated that a loss of from five to eight per cent could be expected. Other types of imperfection may enter, but unfortunately no method of probing the finer details of structures exists, the limit of microscopic vision being several thousand atoms, and only average interatomic separation being supplied by X-ray diffraction-methods. In this regard, experimental helium retentivities themselves offer an indirect means of investigating irregularities in structure.

Variation in the retentive factor for one particular mineral may be due to several causes, to the occasional inclusion of extraneous helium, to leakage of helium due to alteration of the crystal, or to imperfections in growth such as may occur in the formation of secondary minerals.

Contamination by extraneous helium may be due to magmatic helium or to radiogenic helium migrating from rocks. The latter may be expected to follow the easier paths through the interstices between minerals, so that, in the absence of highly radioactive sources, magmatic helium is the probable cause of most spurious high values of the helium index. Trapped gases would be expected to occur in pegmatites and veins formed towards the end of periods of magmatic activity. Experimental results seem to confirm this. High values were obtained in some pegmatites from Fitchburg, Massachusetts, and several carbonates have been found to contain extraneous helium (Table 2). However, minerals in ordinary rocks have occasionally shown some evidence of contamination (Table 1).

In searching for the causes of the variations, examinations of thin sections have indicated a relationship between degree of alteration and helium index. Accordingly, to determine this effect for hornblende, concentrates of this mineral in various stages of alteration were made from several rocks of Algoman age from Red Lake, Ontario [8]. The results are shown in Table 3.

The degree of alteration was obtained by estimating the percentage-alteration of crystals shown in the thin section of each rock. Moderately fresh hornblende shows an appreciable retentivity for helium, but after complete alteration only about five per cent of the helium was found to be present in the secondary minerals. The lowest retentive properties were found when the alteration-products consisted of finely disseminated chlorite with some magnetite. Where secondary hornblende was abundant, the retentive power was also considerably less than for fresh primary hornblende. Petrographically, the former crystals appear quite fresh, but helium leakage indicated that they possess larger channels or spacings within their structures.

Table 3--The effect of alteration on the retention of helium in pre-Cambrian hornblendes[a]

Rock from which concentrate obtained	Degree of alteration	Retentive factor
Granodiorite	40	0.80
Granite	48	0.43
Basic dyke	10[b]	0.38
Granite	60	0.29
Diorite	95	0.09[c]
Granodiorite	95	0.06
Quartz porphyry	100	0.03[c]

[a] Correction applied for feldspar contents of concentrates.

[b] Considerable secondary hornblende present.

[c] Approximate values calculated from impure samples.

The problem of estimating the effects of alteration and other geological factors for purposes of calculating helium-ages from values of the helium index is a difficult one and not yet solved. This subject will be discussed in a future publication.

These researches have been supported by donations from the Viking Foundation and Hans Lundberg.

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THE EFFECT OF PRESSURE ON ACIDITY IN WATER SOLUTIONS

R. E. Gibson and O. H. Loeffler

(Abstract)

The effect of hydrostatic pressure on those dissociation equilibria which give rise to the class of phenomena described by the terms acidity and basicity in aqueous solutions is of considerable interest in studies of phenomena in the depths of the oceans and of the action of water solutions at depths below the surface of the Earth. In this paper the general subject of acid-base equilibria was reviewed, and from theoretical considerations certain conclusions about the general effects of pressure on acid-base equilibria in aqueous solutions were drawn. It was pointed out that important effects of pressure are only to be expected when the solutions contain weak, very slightly dissociated, acids or bases, that the volume-changes due to the electrostriction of the solvent by the ions, which increase as the ionic charge increases and the ionic radius decreases, govern the magnitude of the pressure-effects and that these may be computed with useful approximation from electrostatic theory. It was also emphasized that changes in acidity or basicity of solutions produced by the application of hydrostatic pressure are not expected to have any significant effect on the solubility of sparingly soluble substances in water, in spite of the fact that addition of acids or bases to such systems has a large influence on these solubilities.

Previous work, notably that of E. Brander [Soc. Sci. Fennica Commetationes Phys. Math., v. 6, p. 3, 1932; ibid., No. 17, p. 1, 1936], on the effect of pressure on acid-base equilibria in solutions has all been based on conductivity-measurements. In the present contribution a different method has been employed, namely, the examination of the absorption-spectra of acid-base indicators in different solutions under pressures up to 1,200 atmospheres. Buffer solutions containing phosphates, borates, carbonates, and ammonia have been examined with the help of the indicators cresol red and brom phenol blue. The method is simple, direct, and yields results which agree generally with those of Brander and with theoretical calculations. The results reported are, however, of a preliminary nature because the problem of determining the effect of pressure on the dissociation-constants of the indicators has not yet been satisfactorily solved.

Observations of the change in absorption-spectra of the indicators as the pressure increases confirm the existing ideas that the dissociation-constants of weak acids and weak bases increase with rise of pressure, that in borate, phosphate, or carbonate buffers a change of pressure from one to 1,000 bars increases the hydrogen-ion concentration by approximately 100 per cent and that in ammonia solutions the same rise of pressure decreases the hydrogen-ion concentration by about the same amount.

These effects of pressure on hydrogen-ion concentration may be significant under conditions where the velocities of reactions are of interest.

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SOLUBILITY, TRANSPORT, AND CRYSTALLIZATION BY MEANS OF A VAPOR-PHASE

Earl Ingerson and George W. Morey

(Abstract)

(I) Solubility--By use of a modified "hydrothermal" bomb the solubility of quartz was determined at 300, 400, and 500° C; also the amount of amorphous silica that would go into the vapor-phase under the same conditions. The results are only roughly quantitative: Between one half and one per cent by weight of amorphous silica goes into the vapor-phase at 500° C, with six cc of water in a 20-cc bomb, and about half as much at 400°. About half as much quartz as amorphous silica goes into the vapor-phase at each temperature.

The point at 300° fits Hitchens' curve very well. There is no indication of a break in the solubility-curve at or near the critical temperature.

(II) Transport--With material in solution in the vapor-phase transport takes place merely by motion of the vapor. Deposition may be brought about either (1) by a lowering of the temperature or (2) by a decrease in pressure. These processes are illustrated by deposition of silica in the bomb surrounding a steam-quenching furnace: (1) Near the top where the temperature is much lower than it is in the hot spot; and (2) around any leak where pressure is released.

(III) Crystallization--Many examples of crystallization from a vapor-phase have been noted, but one example is especially interesting in showing a temperature-zoning. In one run of six days at 1,000° C and steam pressure of 3,000 pounds there was a succession of minerals deposited on the refractory tube that carries the electrical leads into the hot spot of the quenching furnace (temperatures, except at the hot spot, are estimated): 1,000° to 900°, sillimanite; 900° to 825°, rutile; 825° to 775°, corundum; 775° to 575°, quartz and amorphous silica; 575° to 500°, amorphous silica. There was overlapping of the zones, especially of quartz and amorphous silica and of rutile and sillimanite. The temperature of the inside of the furnace was everywhere greater than 450° C and crystals formed on the platinum leads as well as on the refractory, so the transport and crystallization must have been by means of the vapor-phase rather than by means of an adsorbed liquid layer on the refractory.

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THE VELOCITY OF THE BIG OBSIDIAN FLOW, BEND, OREGON

Robert L. Nichols

Newberry Crater is about 20 miles southeast of Bend, Oregon. It is a caldera and it has been studied and described by Howel Williams. In this caldera there are three obsidian flows. The most spectacular and interesting of these is the Big Obsidian Flow. This obsidian shows its original flow-features more distinctly, the author believes, than any other obsidian in the United States. It is unweathered and uneroded. It is about a mile long and about 115 feet thick, with an angle of inclination of about 6°. When in motion its specific gravity was not far from 2.5, and, according to the experimental work of A. A. Leontieva, its viscosity was approximately 10^9 poises.

Now although there are many data on the velocity of basalts little is known about the velocity of obsidians as no geologist has ever witnessed an obsidian in motion. However, the velocity of the Big Obsidian Flow may be calculated by means of Jeffreys' formula, as the necessary data are available.

The Jeffreys formula for viscous flow in cgs units is

$$V = g \sin A \; d^2p/3u$$

where V is mean velocity with regard to depth, g is acceleration of gravity, A is angle of inclination, d is depth, u is ordinary coefficient of viscosity, and p is specific gravity. If the above data are substituted in this formula, it is found that the velocity of the Big Obsidian Flow was 120 feet per hour. This is a reasonable figure. The weakness in this calculation is that the viscosity of the flow when it was in motion is not accurately known. If the viscosity was as low as 10^8 poises the velocity would, according to the formula, have been 1,200 feet per hour. If, on the other hand, it was as high as 10^{10} poises the velocity would have been as low as 12 feet per hour. However, the flow probably moved more slowly than the formula indicates, because a carapace of viscous and solid lava formed around the liquid thread and impeded its flow.

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ATMOSPHERIC OXYGEN AND THE VOLCANIC GASES

Robert L. Nichols

Many factors have played a part in the economy of atmospheric oxygen. The green plants, as is well known, take in carbon dioxide and water and under the action of sunlight and in the presence of chlorophyll manufacture and release oxygen. Meteors have temperatures of 2,500° C and above. The water-vapor in the upper atmosphere is therefore partially decomposed into hydrogen and oxygen by impact with meteors. If the upper atmosphere has the high temperatures assigned to it by Martyn (1,000° C) hydrogen will readily escape and oxygen will be added. These high upper-atmospheric temperatures may in themselves be high enough to partially decompose the water-vapor present and allow the hydrogen to escape. The stony meteorites contain approximately 36 per cent of oxygen. Spectroscopic analysis of meteors indicates that they vaporize into their constituent elements. These elements later recombine not only with themselves but also with the constituents of the atmosphere. It may be that in the recombination some oxygen is added to the atmosphere. There is a possibility that a very small amount of water-vapor is dissociated in the upper atmosphere by means of particles and radiation emitted from the Sun and other heavenly bodies. Escape of the hydrogen adds oxygen to the atmosphere. During thunderstorms electrical discharges cause a series of chemical reactions which affect the net amount of oxygen in the atmosphere. They are:

$$N_2 + O_2 \rightarrow 2\ NO$$

$$2\ NO + O_2 \rightarrow 2\ NO_2$$

$$2\ NO_2 + H_2O \rightarrow HNO_2 + HNO_3$$

$$2\ HNO_2 + O_2 \rightarrow 2\ HNO_3$$

$$2\ H_2O \rightarrow 2\ H_2 + O_2$$

$$N_2 + 3\ H_2 \rightarrow 2\ NH_3$$

$$NH_3 + H_2O \rightarrow NH_4OH$$

The decomposition of raindrops and water-vapor into hydrogen and oxygen supplies the necessary hydrogen for the formation of the ammonia. It will be noticed that the formation of the oxides of nitrogen involves a subtraction of oxygen from the atmosphere, whereas the formation of ammonia, because it fixes hydrogen, involves an addition of oxygen to the atmosphere. It is impossible to say what the net result of these reactions is, but they affect, of course, the quantity of atmospheric oxygen.

The volcanic gases have also played a part in the economy of atmospheric oxygen. Throughout geologic time vast quantities of volcanic gases have been added to the atmosphere. These gases have affected the total quantity of oxygen. Although chlorine is one of the volcanic gases, there is no chlorine in the atmosphere. This lack of chlorine is due to the fact that chlorine is very soluble in water, combining chemically with it to form hydrochloric and hypochlorous acids.

$$Cl_2 + H_2O \rightarrow HCl + HClO$$

Hypochlorous acid is unstable, however, and decomposes into hydrochloric acid and oxygen.

$$2\ HClO \rightarrow 2\ HCl + O_2$$

There finally results, as is shown by combining the above equations, a dilute solution of hydrochloric acid and oxygen.

$$2\ Cl_2 + 2\ H_2O \rightarrow 4\ HCl + O_2$$

It seems most probable that chlorine has been emitted from volcanic vents throughout geologic time and that this reaction constitutes a source of atmospheric oxygen. If the above reaction takes place below the Earth's surface, it can account for some of the oxygen emitted from volcanic vents. The chlorine in the ocean has been derived in the main from the weathering of the rocks and from the hydrochloric acid and chlorine emitted from volcanic vents. Unfortunately the relative importance of these three sources is not at present known. If these data were available, the quantity of oxygen produced by the above reactions could be calculated, as the total weight of the chlorides in the ocean is approximately known.

Certain volcanic gases, however, because they can be oxidized, tend to decrease the amount of atmospheric oxygen. They are S, H_2S, SO_2, H_2, CO, C_2H_6, CH_4, C_2H_4, and N_2. They react with oxygen as shown in the following equations.

$$S + O_2 \rightarrow SO_2 \qquad CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$$

$$2\ SO_2 + O_2 \rightarrow 2\ SO_3 \qquad 2\ C_2H_6 + 7\ O_2 \rightarrow 4\ CO_2 + 6\ H_2O$$

$$2\ H_2S + O_2 \rightarrow 2\ H_2O + 2\ S \qquad C_2H_4 + 3\ O_2 \rightarrow 2\ CO_2 + 2\ H_2O$$

$$2\ H_2 + O_2 \rightarrow 2\ H_2O \qquad N_2 + O_2 \rightarrow 2\ NO$$

$$2\ CO + O_2 \rightarrow 2\ CO_2 \qquad 2\ NO + O_2 \rightarrow 2\ NO_2$$

Nitrogen combines with oxygen only with great difficulty, perhaps only in the paths of lightning and meteors. Although the other gases are oxidized much more easily, it is obvious that not all of them are completely oxidized. If the hydrocarbons are not of magmatic origin, and this is a possibility, their oxidation represents no permanent loss of atmospheric oxygen, as oxygen was released in the formation of the cellulose from which by destructive distillation these hydrocarbons were formed. The net result of all these reactions on the quantity of oxygen in the atmosphere cannot be evaluated at present. It is patent, however, that the quantity has been affected by the emission of these volcanic gases.

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ELONGATE INTRUSIONS IN EASTERN CONNECTICUT

David Keppel

(Abstract)

The Monson (Glastonbury) tonalite gneiss intrudes the Brimfield (Bolton) schist in two north-south bands in north-central Connecticut extending northward into Massachusetts east of the Triassic lowland. The intrusion discussed in this paper, mapped as Glastonbury gneiss on the geologic map of Connecticut (1906), is 40 miles long and averages three miles in width; part of the west-central portion is cut by Triassic normal faulting. East of this intrusion a second, even narrower, body of similar gneiss parallels it throughout the entire length, and extends northward to the type-locality of the Monson gneiss in Massachusetts.

The structure of the gneiss seems to be a dome with the axis overturned to the east in the southern portion. In the middle and northern portions both walls of the intrusion dip at angles of 30° to 40° to the west, and the whole structure seems to be a monocline dipping to the west.

Pegmatites cutting the Monson are known to be Late Devonian in age. The age of the schist is unknown, but it is generally thought to be Silurian or Devonian. It is thought that the Monson (Glastonbury) was intruded during the folding and metamorphism of the Brimfield (Bolton) series.

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ALKALINE AND CARBONATE INTRUSIVES IN THE VICINITY OF BANCROFT, ONTARIO

Felix Chayes

(Abstract)

The alkaline intrusives of the Bancroft Area lie along the contact between the "Laurentian" granites and the Grenville marble. Alkaline rocks pass in sweeping arcs about two predominantly granitic areas. The principal alkaline intrusives fall into two quite distinct groups: A series of saturated or nearly saturated rocks ranging in composition from syenite through shonkinite to perknite; an undersaturated group including urtite, ijolite, foyaite, and jacupirangite. Three sill-like bands of marble lie within the alkaline complex. These marble bands are in the main indistinguishable from the Grenville marble immediately south of the complex.

The oval-shaped granite areas are often heavily contaminated with bands and lenses of amphibolite. About these amphibolite impurities the granite develops a marginal syenitic facies and most of the shonkinites have been formed by the intimate mixing of amphibolite and syenitic liquid. The nepheline rocks show no constant association with syenite, granite, or amphibolite. Typically the coarse urtite or nepheline pegmatite lies within limestone. There seems to have been only a small supply of truly foyaitic magma and most of the undersaturated rocks are migmatites or hybrids. Where urtite has been injected into amphibolite, ijolites, and jacupirangites have been formed; where it penetrates syenite, foyaite results.

The alkaline rocks as a whole are younger than the granites of the area but are themselves cut by acid pegmatites. Some of these late pegmatites are albite-aegirine-quartz rocks closely related to the alkaline suite.

The carbonate-rocks of the alkaline complex are intrusive in the sense that they cut and enclose most of the other rocks of the complex, but their intrusive habit is merely the final expression of a long metamorphic history. The region is rich both in primary calcite and in intrusive carbonate-rocks, but the primary calcite is not intrusive and the intrusive carbonate-rocks are not primary.

The granite-syenite-amphibolite association is best explained by the limestone-syntexis hypothesis and nothing in the field-relations of the carbonatite-urtite group contradicts the theory. None of the carbonate is truly magmatic, a small percentage of it is hydrothermal but the vast bulk, including that which forms carbonate-intrusives, is surely metamorphic.

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ORIGIN OF NEW JERSEY MAGNETITE ORES

Donald M. Fraser

(Abstract)

Magnetite deposits found in the vicinity of Dover, New Jersey, and smaller similar deposits occurring in the Reading Prong in Pennsylvania are associated with the Byram and Pochuck gneiss. The Byram granite gneiss has intruded the older Pochuck diorite-gabbro gneiss in an extensive and intimate manner. In this process large quantities of the older formation have been assimilated by the later magma. The crystallization of the resultant mixed magma has given rise to an intermediate type of rock in which the iron-content is lower than would be expected on the basis of the percentage of lime derived from the Pochuck as indicated by the type of plagioclase found in the final product. It is suggested that at the time the Byram invaded the Pochuck and assimilated the latter the iron content was segregated. Later these segregations were either injected into the earlier crystallization products of the magma or were drawn out into elongated ellipsoidal masses during the movement of the magmatic mass as it passed through its final consolidation period.

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GEOMAGNETIC SURVEY OF THE VOLCANIC AREAS OF GUATEMALA

A. G. McNish

In many ways the volcanos dominate Guatemala. They dominate her geography and economy, her people, her plants, and her animals. Even the Earth's magnetism in that country submits to their influence, as may be seen from an isogonic chart (see Fig. 1) based upon the extensive work of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington in that country. Because of the volcanos, or because of the cause of the volcanos, wide-spread anomalies of the Earth's field exist--the isogonic lines which would normally traverse Central America without much deviation swing in great bights to the west as they cross the volcanic rift. Similarly, the other elements of terrestrial magnetism are affected by this conspicuous geological feature.

The close linkage which here exists between numerous natural phenomena and their connection with human life has caused the Carnegie Institution of Washington, in collaboration with other organizations, to undertake a comprehensive study of volcanic action in this region. This study, as has been reported before, is employing geophysical sciences to reveal information on the deep-seated phenomena of which the volcano and its activity are but superficial manifestations. One of the branches of geophysics which has been called on for its contribution to the science of volcanology is terrestrial magnetism.

Regional anomalies in the Earth's magnetism are caused by differences in the magnetic properties of the rocks in the crust of the Earth. It is frequently possible to infer the distribution of magnetic and non-magnetic rocks from the measurable effects which they produce. At normal temperatures volcanic rocks are highly magnetic, but at the temperatures at which lava is extruded from the edifice of a volcano they are non-magnetic. Thus by the magnetic method, possibly better than by any other method, the dispositions of hot and cold underlying rocks may be inferred. In a general way--although the actual interpretation is more complicated than this--wherever the underlying rocks are hot, and hence non-magnetic, a low value of the vertical component of the Earth's magnetic intensity should be observed. With this consideration in mind, a magnetic survey of the region was undertaken.

The results reported in this paper are based upon two seasons' work. Observations during the first season were obtained by the writer in the vicinity of the Volcano Santa Maria (see Fig. 2). Although this was intended for reconnaissance, numerous data of permanent value

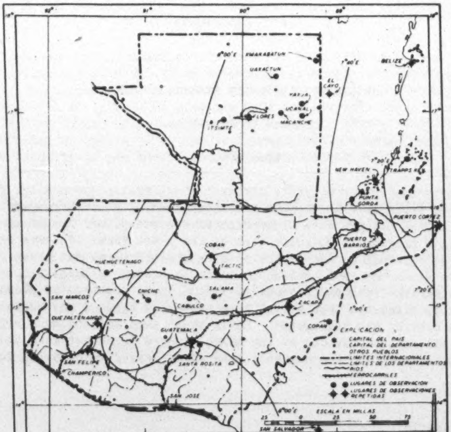
92°
91°
90°
89°
88°
6°00'E
7°00'E
7°20'E
7°30'E
UAXACTUN
EL CAYO
BELIZE
YAXHA
UCANAL
FLORES
MACANCHE
ITSIMTE
NEW HAVEN
TRAPPS
PUNTA GORDA
PUERTO CORTEZ
PUERTO BARRIOS
COBAN
TACTIC
HUEHUETENANGO
SALAMA
SAN MARCOS
CHICHE
CUBULCO
QUEZALTENANGO
ZACAPA
GUATEMALA
COPAN
SAN FELIPE
CHAMPERICO
SANTA ROSITA
SAN JOSE
SAN SALVADOR
EXPLICACION
CAPITAL DEL PAIS
CAPITAL DEL DEPARTAMENTO
OTROS PUEBLOS
LIMITES INTERNACIONALES
LIMITES DE LOS DEPARTAMENTOS
RIOS
FERROCARRILES
LUGARES DE OBSERVACION
LUGARES DE OBSERVACIONES REPETIDAS
ESCALA EN MILLAS
25 0 25 50 75

FIG. 1 — MAPA MAGNETICO DE LA REPUBLICA DE GUATEMALA, 1938
BASADO EN OBSERVACIONES MAGNETICAS HECHAS POR EL INSTITUTO CARNEGIE DE WASHINGTON, 1907-1938

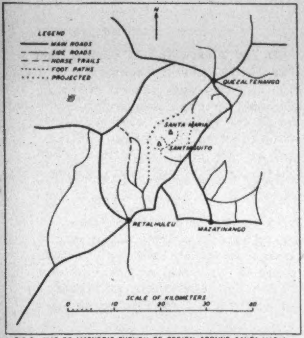
LEGEND
MAIN ROADS
SIDE ROADS
HORSE TRAILS
FOOT PATHS
PROJECTED
N
QUEZALTENANGO
SANTA MARIA
SANTIAGUITO
RETALHULEU
MAZATINANGO
SCALE OF KILOMETERS
0
10
20
30
40

FIG. 2—MAP OF MAGNETIC SURVEY OF REGION AROUND SANTA MARIA (MINOR CURVATURE OF ROADS NOT SHOWN)

were obtained which served not only to delineate the course of future work but to provide material for geological interpretation. During the second season observations were obtained by J. W. Green of the Department of Terrestrial Magnetism, some of which were to supplement the first season's work and others were to ascertain the extent to which the results obtained during the first season were representative of the entire region (see Fig. 3). Altogether over 1,100 observations of vertical intensity at different stations have been obtained. The value of these observations has been enhanced by observations of declination and horizontal intensity at approximately 50 stations.

Speculations on the interpretation of the data so far obtained would be hazardous. What at first seemed to be a purely local effect, it appears, with the acquisition of additional data, may be due to the entire structure which joins the two American continents. Also, the extent to which the magnetic field is due to the volcanism of the region or is due to a major tectonic feature, which has given rise to the volcanism, is as yet extremely uncertain. At present one must be content to present an ordered portrayal of the observations and express a hope that such additional data may be obtained which will clarify our understanding of the problem.

To appreciate the significance of the results (not to mention the difficulty of obtaining the observations) a reasonable knowledge of the topography must be developed. The volcanic rift in Guatemala runs in a northwest-southeast direction parallel with the Pacific Coast about 60 km inland. The coastal plain extends about 40 km from the coast. From this point the land rises with an ever-increasing slope to where the volcanic cones tower nearly 4,000 meters above sea-level and the passes between them attain heights of over 2,500 meters. Inland of the volcanic

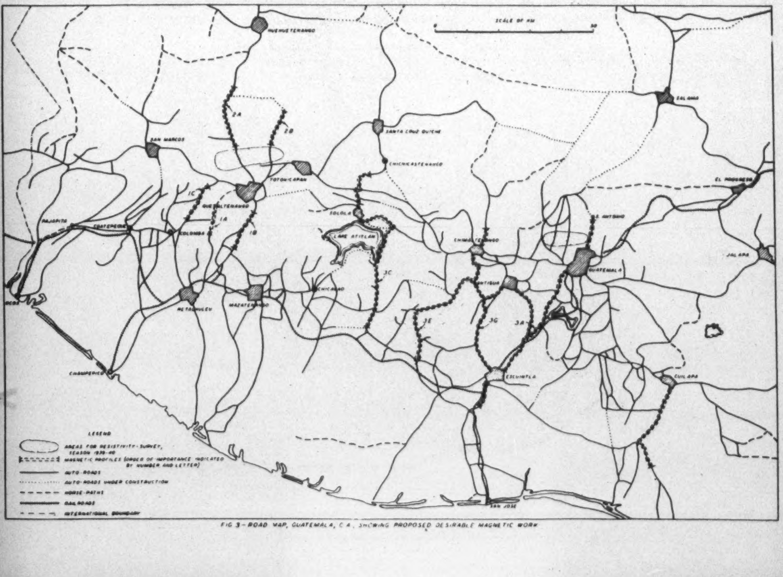
SCALE OF KM
0
50
HUEHUETENANGO
SAN MARCOS
2A
2B
SANTA CRUZ QUICHE
CHICHICASTENANGO
SALAMA
EL PROGRESO
TOTONICAPAN
QUEZALTENANGO
1C
1A
1B
SOLOLA
LAKE ATITLAN
PAJAPITA
COATEPEQUE
COLOMBA
S. ANTONIO
CHIMALTENANGO
JALAPA
GUATEMALA
ANTIGUA
3C
CHICACAO
RETALHULEU
MAZATENANGO
3E
3G
3A
CHAMPERICO
ESCUINTLA
CUILAPA
SAN JOSE
LEGEND
AREAS FOR RESISTIVITY-SURVEY, SEASON 1939-40
MAGNETIC PROFILES (ORDER OF IMPORTANCE INDICATED BY NUMBER AND LETTER)
AUTO-ROADS
AUTO-ROADS UNDER CONSTRUCTION
HORSE-PATHS
RAILROADS
INTERNATIONAL BOUNDARY

FIG 3—ROAD MAP, GUATEMALA, C.A., SHOWING PROPOSED DESIRABLE MAGNETIC WORK

rift extensive plateaus of air-borne volcanic ash are encountered at a height of over 2,000 meters. The volcanic rift is traversed by deep gorges and "barrancas" which render travel difficult even along the highways. Data obtained during the first season's operations permitted construction of a relatively accurate topographical map of the region around the Volcano Santa Maria (see Fig. 4).

A profile of the vertical component of the Earth's magnetism across this rift obtained during the first season reveals low values where volcanic activity is evident (see Fig. 5). As the rift is approached from the high inland plateau, vertical intensity decreases at a somewhat greater rate than that which would be due to simple change in latitude. After dipping sharply to the low but erratic values characteristic of the rift, vertical intensity rises to a pronounced maximum as the coastal plain is approached. The drop from this maximum is at first rapid and then more gradual, and over the coastal plain is still at a greater rate than would be produced by the latitude-effect.

In the volcanic rift difficulty is experienced in determining the "normal" or, more pre-

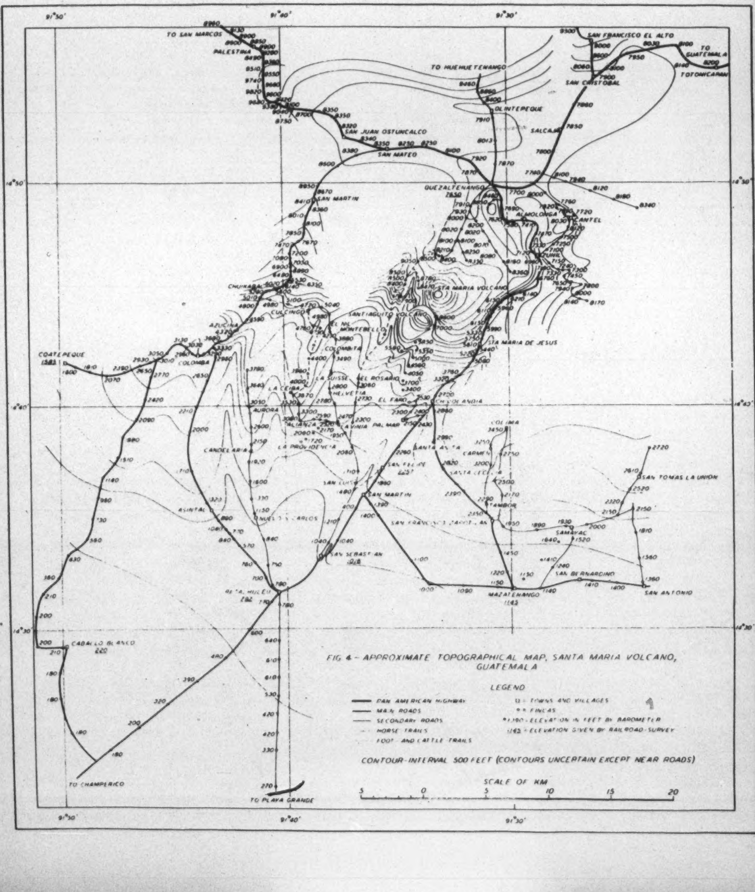
TO SAN MARCOS
PALESTINA
TO HUEHUETENANGO
SAN FRANCISCO EL ALTO
TO GUATEMALA
TOTONICAPAN
SAN CRISTOBAL
OLINTEPEQUE
SALCAJA
SAN JUAN OSTUNCALCO
SAN MATEO
QUEZALTENANGO
ALMOLONGA
CANTEL
SAN MARTIN
ZUNIL
STA MARIA VOLCANO
SANTIAGUITO VOLCANO
CHUVA
CULCINGO
AZUCINA
COATEPEQUE
COLOMBA
MONTEBELLO
COLOMBIA
STA MARIA DE JESUS
LA SUISSE
EL ROSARIO
HELVETIA
LA CEIBA
AURORA
EL FARO
CHOCOLANDIA
LA ALIANZA
LAVINIA
PALMAR
LA PROVIDENCIA
CANDELARIA
COLIMA
SANTA ANITA
CARMEN
SAN FELIPE
SANTA CECILIA
SAN LUIS
SAN MARTIN
SAN TOMAS LA UNION
ASINTAL
NUEVO S. CARLOS
TAMBOR
SAN FRANCISCO ZAPOTITLAN
SAMAYAC
SAN SEBASTIAN
SAN BERNARDINO
MAZATENANGO
SAN ANTONIO
RETALHULEU
CABALLO BLANCO
TO CHAMPERICO
TO PLAYA GRANDE
91°50'
91°40'
91°30'
14°50'
14°40'
14°30'
LEGEND
PAN AMERICAN HIGHWAY
MAIN ROADS
SECONDARY ROADS
HORSE TRAILS
FOOT- AND CATTLE TRAILS
□ = TOWNS AND VILLAGES
• = FINCAS
•1390 = ELEVATION IN FEET BY BAROMETER
1143 = ELEVATION GIVEN BY RAILROAD-SURVEY
CONTOUR-INTERVAL 500 FEET (CONTOURS UNCERTAIN EXCEPT NEAR ROADS)
SCALE OF KM
5
0
5
10
15
20

FIG 4 - APPROXIMATE TOPOGRAPHICAL MAP, SANTA MARIA VOLCANO, GUATEMALA

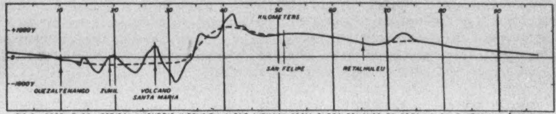

FIG. 5—PROFILE OF VERTICAL MAGNETIC INTENSITY ALONG HIGHWAY FROM QUEZALTENANGO TO RETALHULEU, GUATEMALA (CURVE SMOOTHED BY RUNNING MEANS OF THREE)

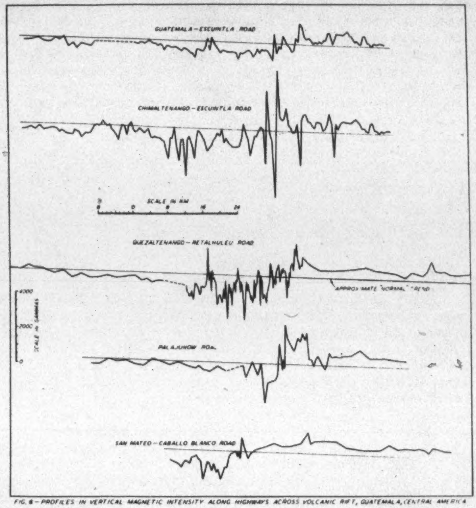

FIG. 6—PROFILES IN VERTICAL MAGNETIC INTENSITY ALONG HIGHWAYS ACROSS VOLCANIC RIFT, GUATEMALA, CENTRAL AMERICA

cisely stated, average value of the field. The method of observation consists in measuring the field at particular points. Owing to the proximity of highly magnetic superficial rocks the observed values of the magnetic force differ considerably within a distance of a few meters. Thus the observer must be continually mindful that his selected stations may not present a fair sample of the magnetic field. Some simplification is obtained by smoothing the data but large effects may be produced by the inclusion or omission of even a single value. Confidence can be placed only in a multitude of data. Accordingly, much of the work during the second season consisted of increasing the number of stations in regions where the magnetic field was disturbed by surface-rocks. Although work during the second season altered the picture presented by the first season's work, all of the main features indicated remained unchanged.

While data obtained during the first season conformed roughly to what was expected on the hypothesis that the volcanic rift was underlain by vast bodies of hot rock, the apparent extension of the effect of the volcanic region far beyond the rift excited considerable interest. With this in view the purposes set forth for the second season's work were to strengthen and extend existing profiles and to establish new ones at other parts of the rift (see Fig. 3).

A more complete picture of the magnetic field near the volcanic rift may now be presented (see Fig. 6). At all points where the volcanic rift is crossed low and erratic values of vertical intensity are encountered. Extension of the profile along the Quezaltenango-Retalhuleu road to sections far beyond those cities strongly suggests that the effects encountered do not have their origin solely in the volcanic rift.

On either side of the rift the fluctuations from station to station are relatively small so that those regions may be regarded as relatively free from local magnetic disturbance. However, the average value of vertical intensity on the coastal plain is nearly 2,000 gammas higher than on the inland plateau although it should be several hundred gammas lower because of the difference in latitude. The significance of such effects in a world-wide magnetic survey are patent--a considerable difference in the assigned values of the magnetic field in that country would be obtained according to whether the observations had been made inland or on the coast, although either region would appear undisturbed to a magnetic observer.

Inference from the magnetic data regarding the disposition of underlying rocks would be hazardous at the present time. Before definite statements can be made the number of observed points must be increased some tenfold to assure that the data represent the average magnetic field and are not strongly affected by purely surface-distributions. There is even reasonable doubt that the method will furnish the desired details regarding the size, form, and depth of magmatic chambers. One clear fact is that large and systematic disturbances of the normal magnetic field are produced by the structure of the Earth's crust in that region which, when an adequate survey has been conducted, will admit of suitable interpretation. Then perhaps information may be revealed of even more far-reaching geological significance than was originally expected.

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GRAVITY-MEASUREMENTS IN GUATEMALA

F. E. Wright

In geology and astronomy the time-element is a dominating factor. From the human standpoint geological processes move along at a snail's pace and ten thousand years is generally too short a time-interval to use in dating geological events. There are, of course, exceptions to this statement, namely, the catastrophic phenomena, such as earthquakes and volcanic eruptions, which occur in the twinkling of an eye and may bring destruction and woe to the inhabitants of a region. Because of their spectacular effects they have long interested the human race, and geologists have given much time and effort to their study.

Special instruments have been developed for the recording of earthquakes at seismological stations, and a great deal of information on the interior of the Earth has been obtained through the use of seismograms. In this respect the seismograph has functioned in geology as has the spectrograph in astronomy to give information regarding distant regions inaccessible to the observer.

In volcanology the problems are of a different kind. Volcanoes are the visible expressions of the movement of subterraneous molten and gaseous material to the Earth's surface. In the majority of volcanoes there is much explosive action, and rock-material is ejected from the volcano as from the mouth of a cannon and in such quantities that precise measurements in the near vicinity of the orifice of the volcano are impossible. Under these conditions the volcanologist is at a disadvantage and cannot gather data of measurement with the ease and certainty of the seismologist. In spite of this handicap a great deal of information regarding the dynamics of volcanic action and of the physical and chemical forces at work has been collected and analyzed. Volcanological stations have been established at a few volcanoes, and more or less continuous records of the activities of these volcanoes have been kept.

For the study of volcanoes, Guatemala, in Central America, is one of the most accessible regions, especially to American volcanologists. Dr. E. G. Zies of the Geophysical Laboratory of the Carnegie Institution of Washington began work there several years ago and chose for detailed observation the Volcano Santa Maria and its more active offspring, Santiaguito, which is still rising and emitting clouds of hot gases. He has collected many samples of rocks and gases from Santiaguito and studied them chemically. He has measured the temperatures of the rock-masses that are being gradually pushed up and out of the Santiaguito rock-mass and has discovered a number of interesting relations. He has been instrumental in having the Department of Terrestrial Magnetism of the Carnegie Institution of Washington undertake certain geophysical measurements in the general region of the volcano. O. H. Gish measured the changes in the Earth's electrical potential at stations within the Santa Maria region; A. G. McNish and J. W. Green made a long series of measurements of the vertical component of the Earth's magnetic field at many stations; W. J. Rooney and J. W. Green made an electric-resistivity survey of the extensive plains of volcanic ash that fill some of the valleys to depths of several thousand feet in the vicinity of Quezaltenango and Guatemala City. Reports on these measurements have been presented before the American Geophysical Union.

Table 1--Gravitational attraction, in milligals, of a cylinder of density = 1 on a point on axis of cylinder produced (Let length of cylinder = t; its radius = r; and distance of top of cylinder below gravity-station = h; volume of cylinder = V)

Section	t, km	h, km	Volume in km^3				
			100 mgl	200 mgl	300 mgl	400 mgl	500 mgl
A	1	0	38.2	39.3	39.8	40.1	40.3
		1	31.2	34.2	35.6	36.4	37.2
		5	12.7	18.2	21.4	23.6	25.2
		10	5.0	8.6	11.2	13.4	15.1
	5	0	80.6	101.7	114.4	123.4	130.1
		1	50.5	68.1	86.4	96.6	104.5
		5	12.1	22.0	29.0	37.8	45.6
		10	4.2	8.9	12.1	15.7	19.1
	10	0	68.2	92.7	110.0	123.7	135.1
		1	37.8	59.9	76.4	89.8	96.8
		5	11.3	16.4	23.6	30.4	36.6
		10	3.3	6.5	9.6	12.6	15.6
Section	t, km		r, km	r, km	r, km	r, km	r, km
B	1		5.64	7.98	9.77	11.28	12.62
	5		2.52	3.57	4.37	5.05	5.64
	10		1.78	2.52	3.09	3.57	3.99

As a further method of attack Dr. Zies suggested that gravity-measurements be made in this region. At first sight it might appear futile to attempt a series of gravity-measurements around Santa Maria. The region has not been surveyed topographically; no adequate geological map of the region has been made; the rock-types differ greatly in composition and in degree of compactness. Under these conditions the effects of the terrain near a given gravity-station on the observed gravity-value can be only roughly estimated and the computation of isostatic or other anomalies would serve little purpose. However, if a network of accurate gravity-stations were to be established in the Santa Maria volcano region and the measurements were repeated at these stations periodically, changes in the values of gravity at the stations might serve to indicate the migration of the molten rock below the volcano toward the surface. The density of the molten magma is probably different from that of the surrounding country rock; its approach toward the Earth's surface might well produce an effect on the observed gravity-values, especially those at gravity-stations nearest the underlying molten mass. In establishing each gravity-station of the series its exact elevation should be determined in order that, if a change in the observed value of gravity is obtained at a given station, it will be possible to ascertain if the change is due to uplift or downwarp of the surface at that point or to shift in underlying rock-masses and the upward movement of the molten mass. The network of gravity-stations should be sufficiently close to enable conclusions to be drawn regarding the exact area below which the magma is rising.

If we assume the magma-chamber to have roughly the shape of a vertical cylinder and the difference in density between magma and surrounding country rock to be unity, it is a simple task to compute the gravitational attraction of the magma-mass on a point directly above the magma-chamber. The results of the computations for magma-chambers of volumes ranging from 100 to 500 km^3 and for various distances below the surface and for various shaped cylinders are listed in Table 1. They show that the changes in gravitational attraction are quite appreciable as the top of the magma-chamber approaches the Earth's surface. Take, for example, a cylinder five km thick and five km in diameter; its gravitational attraction at the station is 4.2 milligals when the top of the cylinder is ten km below the station; it is 11.8 milligals when the top of the cylinder is at five-km depth; 50.0 milligals for the top of the cylinder at one-km depth; and 80.1 milligals when it is at the surface. As the magma moves upward its gravitational effect at the gravity-station changes markedly and in easily measurable amounts.

The ideal case of a cylinder was chosen to facilitate the computations. The actual shape of the magma-chamber is certainly not so simple, and the assumed difference of unity between the density of the magma and that of the country rock is probably too high. If the gravity-station is not on the produced axis of the vertical cylinder the resulting gravitational attraction by the magma-chamber is less [see note below]. If the density-difference is less the gravitational attraction is less in proportion to this difference. In a volcanic eruption such as that of Santa Maria, however, vast amounts of material are moved upward and these should show detectable changes in gravity at stations not too far away from the advancing magma.

[Note: I am indebted to C. H. Swick (letter of May 8, 1941) for the results of recent computations made at his request by J. A. Duerksen of the United States Coast and Geodetic Survey on the change in gravitational attraction as the gravity-station is moved away from the produced axis of a vertical cylinder of density unity as shown in Table 2.]

Table 2

Top of cylinder below station	Distance of gravity-station from produced axis of cylinder			
	0 km	1/2 km	1 km	2 km
meters	mgl	mgl	mgl	mgl
Radius of cylinder, 1/2 km, length, 5 km, and volume 3.93 km^3				
0	20.1	12.3	4.5	1.6
100	16.4	10.5	4.4	1.6
1000	4.3	3.7	2.8	1.5
2000	1.9	1.8	1.6	1.1
5000	0.5	0.5	0.5	0.4
Radius of cylinder, 1 km, length, 5 km, and volume 15.71 km^3				
0	37.6	34.5	22.9	7.4
100	33.8	30.6	21.0	7.5
1000	14.1	12.7	10.8	6.5
2000	7.1	6.5	6.1	4.8
5000	2.1	2.0	2.1	2.0

The proposed network of stations should be selected with reference not only to gravity but to magnetic and other measurements of those physical quantities that may be influenced by movement of subterranean masses in the vicinity of the volcano. Periodic occupation of these stations with the several types of field-apparatus would enable the observer to detect areas in which changes are taking place and thus to obtain information regarding subsurface movements. In the study of an active volcano the dynamical aspect of the problem is potentially more fruitful of results than the static. This statement applies both to physical and to chemical studies. It would appear that at each volcanological observatory emphasis should be placed on the dynamical phases of volcanic activity and that each field-station, which is to be occupied repeatedly, should be chosen with reference in part to its accessibility. Differential movement of the surface of the ground within the given area should be determined by periodic occupation of each station with a precise level.

Although this proposal to establish a network of gravity-stations about a volcano has elements of uncertainty regarding the exact degree of change in gravity at a given station, the method can be applied without difficulty and at small expense and would seem to be worth while in a volcanic area of sufficient activity to justify a permanent volcanological observatory.

Preliminary to the establishment of a network of gravity-stations in the vicinity of a large and active volcano, a base-station should be occupied with a gravity pendulum-apparatus to serve as reference-point for measurements with a gravity-meter. The base-station should be located in a place free from volcanic activity.

It was my task a year ago to make gravity-measurements with a pendulum-apparatus at Guatemala City and at Quezaltenango in Guatemala, Central America. The United States Coast and Geodetic Survey generously loaned the Carnegie Institution of Washington a Brown gravity pendulum-apparatus for the purpose, which had just been returned from a field-trip of 18 months. After a brief course of instruction in the use of the apparatus by Lieutenant Hoskinson, during which the base-station at Washington was occupied, we had the instrument shipped to Guatemala. In Guatemala City measurements were made at the National Observatory (Meteorological), which, unfortunately, is located very near the central commercial transmitting and receiving radio station of Tropical Radio through which all radio messages for Central America pass. As a result, reception of radio time-signals from Washington was difficult because of interference; in addition there was generally electrical static interference each night from midnight to daylight and many runs were lost because of inability to obtain satisfactory radio signals. Other troubles were also encountered; but measurements of a fair degree of accuracy were obtained and were in fair agreement with determinations made previously by Dr. Pedro Sanchez and by a gravity-party of the Royal Dutch Shell Company with a gravity-meter. The values obtained were the following:

Station	Observer	Year	Gravity, gals	Elevation, meters
Guatemala City	Pedro Sanchez	1935	977.973	1,494
	Shell Company	1938	977.986	1,494
	F. E. Wright	1940	977.985	1,494
Quezaltenango	F. E. Wright	1940	977.781	2,384

The gravity-values obtained at Guatemala City and at Quezaltenango are only of a fair degree of accuracy because of a rather large correction for flexure, due to the thin layer of cement paving of the floor in the basement of the observatory. This situation was unfortunately not noted until after the measurements had been completed.

It is a pleasure to acknowledge the courtesy of the officials of the United States Coast and Geodetic Survey, Rear Admiral L. O. Colbert, Captain C. L. Garner, Lieutenant A. J. Hoskinson, and C. H. Swick, and of Director Sául de Léon and Senor C. Urrutia of the Observatorio Nacional Meteorológico at Guatemala, and of Director H. F. de Léon of the Observatorio Meteorológico de Occidente of Quezaltenango. Without their cordial cooperation and aid, satisfactory measurements could not have been made.

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VOLCANIC ACTIVITY AT SANTA MARIA IN 1940

E. G. Zies

(Abstract)

In this paper a brief outline of the growth of the volcanic dome of Santiaguito in Guatemala and the chemical aspects of its fumaroles was presented.

A good pictorial record of the growth was obtained by the Swiss observer Hurter from the time of its first appearance in August of 1922 up to October 1925, when steady extrusion of the viscous andesitic lava had built up the dome to a height of approximately 1,000 feet. Slow extrusion of lava from the western flank has continued since 1925 and has contributed to a great increase in the bulk of the dome. At no time has the lava issued freely. It is inferred that the lava has lost most of its gas content before reaching the surface and has thereby lost much of its potential fluidity. An outstanding event in the history of the dome was the explosive eruption of 1929 that took place on its southern slope. A glowing cloud emerged and destroyed much of the vegetation on the lower slope of the parent volcano, Santa Maria.

The dome has been investigated on a number of occasions by various members of the Carnegie Institution of Washington, and the results of their work have been briefly reported in the *Transactions* of the American Geophysical Union. More detailed reports will be presented when the results have been subjected to more thorough investigation.

Chemical aspects--In 1941 the chemical aspects of the fumarolic activity on the eastern slope were studied more thoroughly than was possible during the previous visits to the dome. It was thought that the loose coherent mass of andesitic blocks permitted ready access of air which oxidized the sulfur and hydrogen sulfide in the escaping steam to sulfur dioxide and to sulfuric acid. The incrustations formed by the action of the vapors on the rocks formed sulfates of the bases and left much of the silica as opal. No other acid radicals were found. In 1941 it became possible to work at the fumaroles without exposing the worker to great hazards. The steam was condensed and subsequent investigation in the laboratory showed that no hydrogen sulfide was present, thus confirming the earlier findings. It was also determined that hydrochloric acid was present in addition to the sulfur dioxide and sulfuric acid found at previous times. Likewise small but easily determinable amounts of hydriodic acid were found. Neither chlorides nor iodides are present in the incrustations. This is not surprising in view of the preponderance of and the chemical activity of sulfuric acid at 350° C, the temperature of the acid steam to which the lava-blocks at the surface are exposed.

A group of fumaroles about 300 feet higher than the ones just referred to was observed on previous visits to the area. They are located on a very steep slope (gradient of about 40°) and are intensely active. The choking character of the escaping steam prevented close inspection. In 1941, however, means were found for studying this group. Abundant sulfur was present and cemented the rock-fragments that mantle the area around the orifices of the steam-vents. Obviously we have here a different chemical environment and one that falls more in harmony with the activity usually associated with secondary volcanic phenomena. It is inferred that the channels in the lava are not pervious to the air and are directly connected with the source of supply of the escaping vapors. Preliminary analysis of the condensed steam revealed the presence of hydrogen sulfide, hydrochloric acid, small amounts of sulfuric acid and minute but easily determinable amounts of hydriodic acid. The incrustations found in the throat of the vents are not so strongly altered as those found in the lower group of fumaroles.

All incrustations are being subjected to chemical and optical investigation in the laboratory, and particular attention is being given to the manner in which the rocks themselves have been altered. A suite of samples showing progressive alteration was collected for this purpose. A qualitative examination for metallic constituents such as lead, tin, molybdenum, copper, and zinc was made, but only molybdenum has been found in easily detectable amounts. In this respect the incrustations differ greatly from those found in the volcanic area of the Valley of Ten Thousand Smokes.

Considerable laboratory work remains to be done. The detailed account of the results of the various expeditions to the active dome of Santa Maria and the implications of the chemical and physical investigations will be presented after this work is completed.

Geophysical Laboratory,
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Washington, D. C.

AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30 - MAY 3, 1941

SECTION OF TECTONOPHYSICS

REPORTS AND PAPERS

WASHINGTON, D.C.
MAY 1, 1941

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REPORTS AND PAPERS, SECTION OF TECTONOPHYSICS
NATIONAL ACADEMY AND RESEARCH COUNCIL BUILDING
9:00 A.M. AND 2:00 P.M., MAY 1, 1941

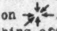
DEFORMATION OF MARBLE UNDER TENSION AT HIGH PRESSURE

James R. Balsley

Geologists have for a long time speculated upon the strength and mechanism of deformation of the rocks they have seen folded and faulted throughout the world. Much is gained from the study of these phenomena in the field, but little of a quantitative nature, for the physical and chemical environment can only be surmised. Recognizing this, F. D. Adams was led to perform laboratory experiments on natural materials under controlled conditions. This work has been continued, notably by von Kármán, Bridgman, and Griggs, and a great deal of valuable information obtained concerning the strength and mechanism of deformation of various rocks in different pressure, temperature, and chemical environments.

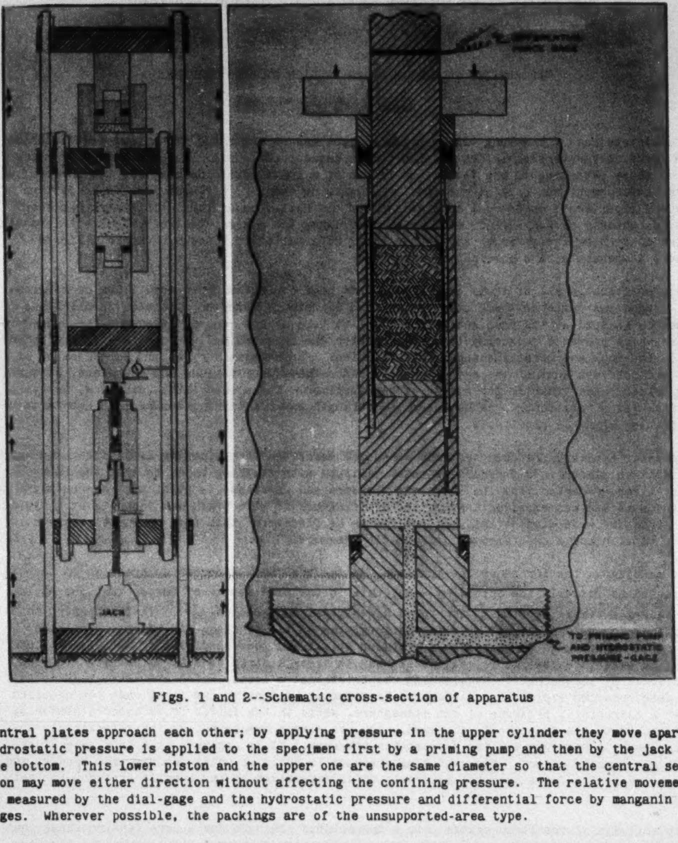
But practically all of these experiments have been conducted under conditions of compression. Griggs has performed some tensile tests on limestone, using an apparatus in which the specimen is grasped at the ends and pulled. But in this device, the specimen must be shaped in a manner which prevents jacketing it. This permits the pressure-medium to enter the cracks and pores in the rock and greatly change its properties. Furthermore, any slight imperfection of fit of the specimen against the grips causes a concentration of stress, and therefore, rupture at the holder rather than in the middle of the specimen. These experiments did show, however, that there was a relationship between tensile strength and confining pressure and that further investigation might be profitable.

Somewhat earlier, Bridgman had discovered and described the "pinching-off" effect, in which a specimen was placed in a pressure-cylinder equipped with stuffing boxes so that the ends of the test-piece projected from it. When the pressure was increased, a point was reached where the specimen broke and was expelled through the stuffing boxes. The break was found to be a typical tension-fracture, and when he analyzed the forces he discovered that they could be resolved into a simple tension and a superimposed hydrostatic pressure.

If we diagram the forces on the specimen, we see that they comprise compression in two directions and no force in the third: But this is the same system of forces that one would get by adding a simple tension and three dimensional compression . It is apparent that the vertical forces cancel, and give the force-system of the pinching-off effect. The same forces could be produced by squeezing a cylinder of clay in your hand, but if one extends this analogy, he discovers that it is relatively easy to break a strip of clay by pulling its ends, but difficult by squeezing it. Neglecting the frictional effects, which are very great in the latter case, one can explain the difference by remembering that in the first case the specimen is under a hydrostatic pressure of one atmosphere, while in the latter it is under a confining pressure equal to the squeeze of your hand. You are simply demonstrating the relationship between the tensile strength and the hydrostatic pressure. It is apparent that this type of experiment has a major defect. The confining pressure is built up until the specimen breaks, and this is not variable for a specific material; it is determined by the tensile strength of that material.

The analysis of the force-system into a hydrostatic pressure and a pure tension shows that a similar set-up can be used to determine the relationship of hydrostatic pressure to tensile strength. Griggs has designed and developed this apparatus and it was used in these experiments. Consider again the clay, but now not only squeeze in two directions but three. We can apply as great an amount of hydrostatic pressure as we wish without fracturing our material. If we release the pressure in one direction we encounter the pinching-off effect--a hydrostatic pressure superimposed upon a pure tension. The original hydrostatic pressure is and as we release pressure, we arrive at which is equal to the original hydrostatic pressure plus a tension numerically equal to the amount of pressure being released. It is apparent that we can now build up our hydrostatic pressure to any desired point, and determine the tensile strength by release of pressure in one direction.

That is what is done in the actual apparatus (Fig. 1) which has been built by Griggs and financed by a grant from the Penrose Fund of the Geological Society of America. It permits both tension and compression in the central section. By applying pressure in the lower cylinder the



Figs. 1 and 2--Schematic cross-section of apparatus

central plates approach each other; by applying pressure in the upper cylinder they move apart. Hydrostatic pressure is applied to the specimen first by a priming pump and then by the jack at the bottom. This lower piston and the upper one are the same diameter so that the central section may move either direction without affecting the confining pressure. The relative movement is measured by the dial-gage and the hydrostatic pressure and differential force by manganin gages. Wherever possible, the packings are of the unsupported-area type.

In practice, the press is pressure-locked and the confining pressure built up. Pressure is then applied to the upper cylinder and the plate moves down until the specimen in its holder strikes the shoulder. As the plate continues to move, the pressure is decreased in the vertical direction, stretching the specimen until rupture occurs. In the actual apparatus (Fig. 2) a packing press is used to apply pressure to the upper packing, shown by the force arrows in the sketch.

The specimen is jacketed with an annealed copper tube which is soldered to the upper piston (Fig. 1). As the material is stretched, it decreases in diameter and, unless special steps are taken, the copper shears at the sharp corner created because the marble shrinks more than the steel. This is partially overcome by the use of steel end pieces which bend with the marble and round the corner. It is right here that the major difficulty is encountered for in all the high-pressure runs the specimen broke at the end due to the inability of the jacket to keep pace with the elongation of the specimen. This elongation is clearly shown on a specimen which has been stretched 24.7 per cent at 10,000 atmospheres (Fig. 3). Although plastic deformation in tension has been shown by Braudtzeg in concrete and by Schmidt in salt, this is the first time

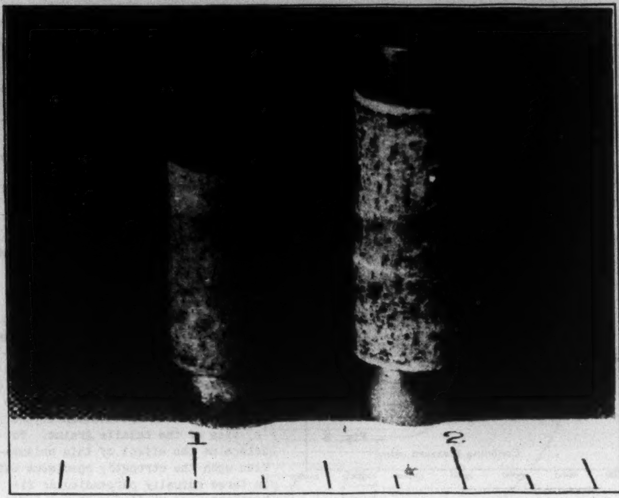


Fig. 3--Marble stretched plastically in tension under 10,000 atmospheres confining pressure (specimen at left is size before extension)

that it has been demonstrated in rock. This shows clearly the decrease in diameter of the specimen and the way in which the end pieces have bent in to accommodate this change. This elongation is in itself surprising, but even more so is the fact that this specimen withstood a tensile stress of 4,800 kg per cm^2, 16 times the compressive stress it can withstand at atmospheric pressure. Griggs and others have already investigated the great increase in compressive strength with increase in confining pressure. These curves are similar to the stress-strain curves of metals with the elastic deformation, yield-point, and plastic flow, and in some cases, decreasing strength immediately before rupture. The curves for the behavior of marble in tension are strikingly similar to these (Fig. 4). The tremendous increase of strength with increased pressure is apparent; the compressive strength at atmospheric pressure is shown by the small line. Though an increase was expected, the amount is surprising; in fact, new pistons of high-tensile-strength steel had to be made after the original piston broke, with a typical tension-fracture. The marble at 10,000 atmospheres confining pressure was stronger in tension than the steel. It is an interesting paradox that there were several surfaces across which there was no cohesion that were also stronger than the steel. Note again that the specimens at the lower pressures show decreasing strength immediately before rupture as do many metals. It is these specimens that broke in the middle and showed apparent necking down at the break. The specimens that do not show this, on the other hand, all broke at the end pieces for the greater elonga-

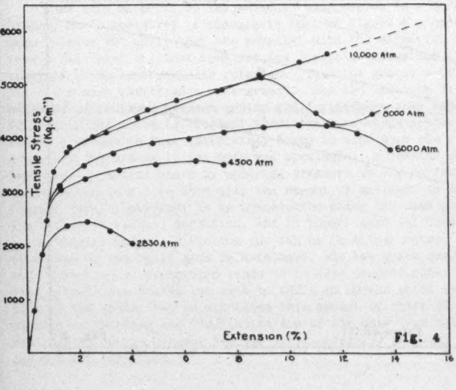


Fig. 4

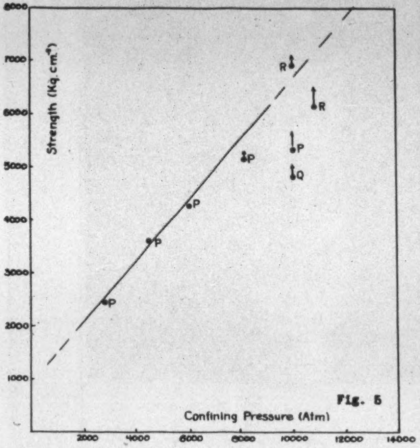


Fig. 5

tion in these cases was too much for the jacket to accommodate. The final points in these curves then are not true indications of the ultimate strength, but are more in the nature of measures of perfection of experimentation. In the compressive experiments, it has been possible to determine the exact nature of the relationship of compressive strength to confining pressure, for here jackets were not used. The relationship of tensile strength to confining pressure is still confused by this experimental difficulty, so only the first three points can be considered the true strength (Fig. 5). The line drawn is merely an indication, but even so it is different from that in compression, for in those experiments no jacket was used and the pressure-liquid was free to enter the open spaces in the rock. The points are labelled because the original marble has a pronounced orientation of the "c"-axes of the calcite grains. To determine the effect of this orientation upon the strength, specimens cut in three mutually perpendicular directions were studied. It was found that the specimens which had a majority of the "c"-axes parallel to the direction of tension, those marked "Q", were weakest. Those marked "R" and "P" both had the "c"-axis maxima perpendicular to the direction of tension, but other factors in the fabric were responsible for the greater strength of the "P"-specimens. Figure 6 shows this for specimens at ten thousand atmospheres. Repeat-experiments have duplicated these curves.

The reason for these differences in strength is tied up in the method of deformation and this in turn related to the individual grains of the aggregate. To study this, one must turn to structural petrology and the system of petro-fabric analysis. This investigation of the deformation of marble is being carried on by Dr. Eleanora Knopf and it was largely at her instigation that these experiments were performed. The results described here can be in no way considered final but are simply indications. She is continuing her more detailed study of the fabric of these deformed specimens.

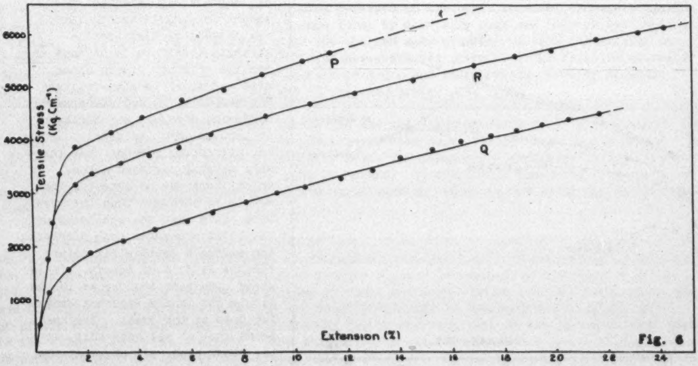


Fig. 6

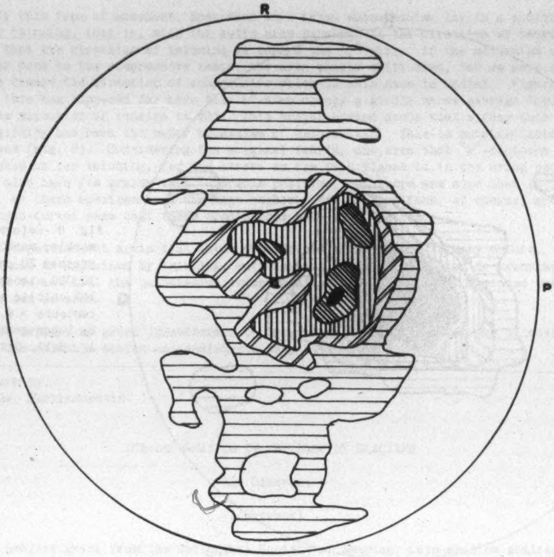


Fig. 7--Undeformed Yule marble; 209 calcite axes, contours 9, 7, 5, 3, 1 per cent rotated (E. B. Knopf)

It is apparent by comparing the fabric of the undeformed Yule marble (Fig. 7) to that which has undergone elongation that there has been considerable change. The character of this change is studied by measuring the attitude of the optic axis of the calcite by means of the universal stage and plotting these on a stereographic projection. The field of points is then contoured according to the density of the points.

When this material is subjected to compression in a direction parallel to P as was done by Griggs, the orientation is changed to that of Figure 8. Here practically all the optic axes have been rotated 90° until they are parallel with the direction of compression. To determine the reason for this, one must consider the possible mechanisms of rotation of the axes. The most apparent is by intergranular rotation. Thus the grains move one against the other till they reach the most comfortable arrangement. But the sections of the deformed rock show very little evidence of crusning between grains and furthermore they had no apparent elongation that could be used by the force to reorient them; they are roughly spherical. We must look to another cause, a mechanism that immediately comes to mind when one recalls the great number of parallel cracks in the grains in the deformed specimens. A familar demonstration of this is mechanical twinning of calcite where by applying pressure in the correct way a portion of the crystal can be caused to twin. In this slip the amount of movement is controlled and the axis moves 52°5. Another type of movement is by translation along the same planes. In twinning the movement is restricted in amount, direction, and in sense, that is, toward the "c"-axis, but in translation it is limited only in direction and can be in either sense. In slipping along these planes, the direction of the optic axes is unchanged, but the grain-shape is changed; it is elongated and this direction of elongation tends to be kept perpendicular to the direction of compression. This orientation causes the axis to shift an amount which is dependent upon the amount of elongation of the grain, but in all cases this amount of shift is much less than that in twinning. The results of twinning and translation are of the same type with a quantitative difference. To distinguish surely between the two it is necessary to study the sections statistically and this has not yet been done.

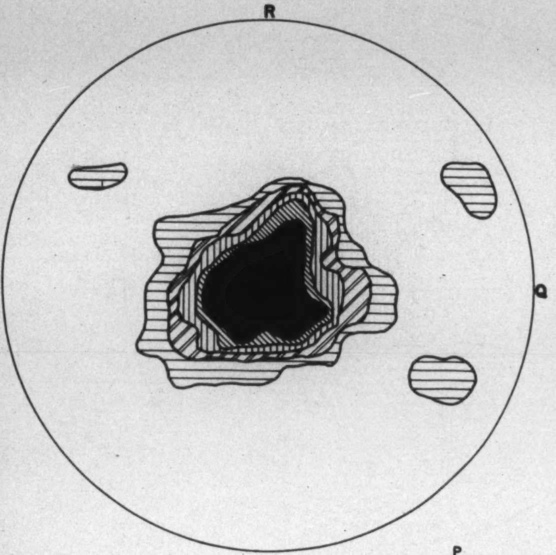


Fig. 8--Deformed Yule marble; marble compressed 30 per cent, 10,000 atmospheres, 163 calcite axes, contours > 9, 7, 5, 3, 1 per cent (Snively, Bell, Griggs)

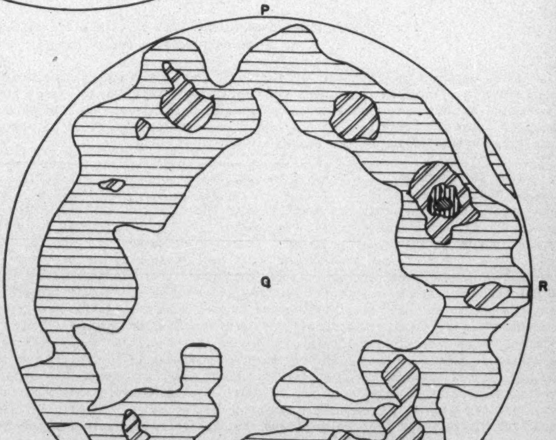


Fig. 9--125Q; 200 calcite axes, contours 7, 5, 3, 1 per cent

To verify this type of movement, specimens were taken whose maxima lay in a position most favorable for twinning, that is, with the optic axes parallel to the direction of tension; for we have seen that the direction of twinning is toward the "c"-axis. If the mechanism operates here as it has done in the compressive tests, the axes should shift down, for we have seen that the axes move toward the direction of compression which in this case is radial. Figure 9 shows clearly that this has happened for here the "c"-axes occupy a girdle whose average angular distance from the direction of tension is 63°. This proves beyond doubt that either twinning or translation-gliding has been the major mechanism of deformation. This is substantiated by the strength-curves (Fig. 6). Considering the original fabric, one sees that "P"-sections have the poorest orientation for twinning, for the stress on the twin planes is in the wrong sense. The "R"-sections also have few grains in a favorable position, but there are more than in the "P"-sections, so these specimens are somewhat weaker. The "Q"-sections, of course, are weakest, and the strength-curves show that these predictions have been verified.

It must be pointed out again that these conclusions are of a preliminary nature. Clearly the phenomena can be explained by twinning, but they can also be attributed to translation-gliding and it is not till the painstaking investigations of Dr. Knopf are finished that the complete picture can be seen.

I wish to express my great indebtedness to Griggs and Bridgman for the use of their equipment and for the valuable advice and assistance they have given me.

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ICE-DEFORMATION IN THE FLOW OF GLACIERS

Max Demorest

(Abstract)

Under a project-grant from the Geological Society of America, thin-section studies were made of ice from the glaciers of Mt. Rainier. Of greatest interest were observations of ice-granules along and across "fault-planes" in the glaciers. In many of the cases observed no true fracture or movement on discrete planes seems to have occurred. It appears probable that differential movement progressed by a combination of inter- and intra-granular adjustments which involved basal slip, distortion of the crystal lattices, and one or more types of recrystallization.

One of the types of recrystallization that is thought to be most significant is here tentatively called "instantaneous recrystallization." According to the author's hypothesis (and it is only a hypothesis) this recrystallization is conceived of as being similar to the instantaneous atomic and molecular reorganization that produces both twinning and polymorphic changes in many minerals. In glacier-ice, however, neither twinning nor polymorphic changes seem to occur. The atomic and molecular reorganization simply reproduces the same lattice-structure but causes a change in the grain-shape and orientation such that stresses are relieved. Evidence from thin-section studies seems to show that this sort of recrystallization is preceded by distortion of the lattice (shown by undulatory extinction). Distortion, in turn, causes the internal energy of the lattice to be increased, and when the energy reaches a certain critical value instantaneous recrystallization results.

Fabric analysis shows that where a constant direction of stress-application is long-continued, recrystallization ultimately causes all the grains to become oriented with their basal planes approximately parallel to the direction on maximum shear-stress. In such positions deformation proceeds most easily by basal gliding with the result that instantaneous recrystallization is no longer necessary to the deformation-process.

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AN EXPERIMENTAL APPROACH TO DYNAMIC METAMORPHISM

David Griggs

Introduction--In the study of rock-deformation it is necessary that the physical properties of rocks be studied under all conditions of environment which are thought to exist in the Earth's crust. As the author has pursued this line of investigation, it has been possible to add successively to the factors of environment. At the present time apparatus is in operation in which all the variables may be handled simultaneously, within moderate ranges, as follows:

(1) Confining pressure (liquid pressure)	0 to 1,000 atmospheres
(2) Shear-stress	0 to the strength of the material
(3) Temperature.	0° to 500° C
(4) Chemical environment	aqueous solutions possible
(5) Time	all factors may be held constant over any desired interval

With the attainment of high temperatures in the presence of aqueous solutions, it has been found difficult to make the usual measurements of physical properties of the solid state, such as strength, equivalent viscosity, etc. This is largely because the rocks no longer react as a strong solid, but tend to move readily in a process of recrystallization combined with fracture.

It is at once apparent to a geologist that we are here dealing with an environment similar to that thought to exist under conditions of low-grade dynamic metamorphism. Hence it was thought worth while to make an attempt to produce the mineralogical changes found in low-grade metamorphic zones. While much previous laboratory work has been done in this field, little of it has been systematic. The particular additional factor which is available with the present apparatus that has not been tried before is the shearing stress. It was thought that some changes which would not take place in mixtures under high temperature, confining pressure, and in the presence of water might occur when the solid was subjected to shearing stress of a high intensity.

Attempt to produce metamorphic changes--Systematic experiments throughout the range of temperature and pressure available have not been completed. Table 1 shows what experiments have been tried. It requires little additional comment.

One development of possible geological significance is the apparent formation of serpentine from olivine under shearing stress, but not under hydrostatic pressure, all other conditions being essentially similar. This is in accord with the common geological observation that alteration of olivine to serpentine occurs more readily in zones of high shearing strain.

Perhaps the most significant thing is the lack of mineralogical changes under the conditions of these experiments. There are three plausible reasons why the common low-grade metamorphic changes have not occurred: (1) The duration of the experiment was insufficient; (2) the temperature was not high enough; (3) the chemical environment was not similar to that in nature. The first two may be tested to a certain degree with ease. Since they work hand in glove, an increase in temperature will produce the same effect as an increase in time. Thus it may be possible to combat the nemesis of geologic time. The last factor--chemical environment--is one of much more uncertainty. A promising mode of attack is experimentation with the common permeating volatiles which leave their traces wide-spread in nature, namely, boron and fluorine. It is hoped that the present experiments may soon be extended to higher temperatures, longer times, and more complex chemical environments.

Behavior of quartz--Ingerson has measured the solubility of quartz up to 500° C, as shown in Table 2. Thus we see that, at these temperatures, quartz is a fairly soluble substance.

Table 2

Temperature	Solubility, parts per 100
300°	0.1
400	0.15
500	0.3

In the present experiments, it was learned that quartz becomes very mobile under shear-stress. When an aggregate of sand-grains was subject to compaction, shortening occurred at a rate which decreased inversely in proportion to the time. Microscopic study demonstrates that this deformation takes place by solution at the points of contact (and hence stress-concentration) and deposition in the voids. As deformation proceeds, the stress-concentrations are relieved, and the rate of solution decreases. If now the stress is increased, by an increase in loading, then the process is accelerated, and a new compaction-curve is followed.

Table 1

Experiment	Original powder	New mineral	Solution	Temperature, °C	Pressure, atm.	Com. stress, kg/cm^2	Type (see note)	Appr. shortening, pct	Duration, days	Remarks
CPT-22	Shale	None	H_2O	425	1000	320	C	10	0.3	No new minerals or change in grain-size discerned
CPT-23	Calcite	None	H_2O	425	1000	1000	C	50	3.1	Powdered calcite shows no recrystallization; highly twinned
CPT-25	Calcite	Dolomite	$MgCl_2$	300	1000	0	H	..	1.0	Pseudomorph of dolomite after calcite; has structure of original calcite rhomb
CPT-26	Andesine	Hibschite(?) Apophyllite(?)	KOH	300	1000	0	H	..	1.0	Identification of new minerals by John Lyons on optics--tentative
CPT-27	Andesine	None	H_2O	430	1000	700	C	30	1.6	Isometric $X\ell$, μ =1.525, only new mineral; mostly unaltered andesine
CPT-36	Andesine	None	H_2O	340	500	2100	S	40	0.007	Surface in contact with piston oriented; felspar unaltered
CPT-28	Biotite	Possible stevensite	H_2O	425	1000	700	C	10	1.4	Mostly unaltered biotite
CPT-43	Biotite	None	H_2O	340	500	1000	S	70	0.16	Mostly unaltered biotite
CPT-31	Nepheline	None	H_2O	300	1000	0	H	..	1.55	Unaltered; cancrinite in original
CPT-44	Nepheline	Possible davyne	H_2O	340	500	1000	S	85	0.03	All cancrinite gone; seems to be altered to davyne, ω = 1.516
CPT-33	Olivine	None	H_2O	300	1000	0	H	..	1.0	Olivine unaltered; minor chromite, felspar, and serpentine unchanged
CPT-46	Olivine	Serpentine(?)	H_2O	340	500	1000	S	80	0.06	Olivine has surface-alteration which looks like serpentine
CPT-45	Quartz and clay	No change	H_2O	340	500	1000	S	90	0.05	Clay lubricates quartz-grains and gives orientation by grain-shape
CPT-55	Quartz and clay	No change	H_2O	400	1000	1200	S	7	0.75	No quartz-calcite interaction; quartz floating in matrix of deformed calcite
CPT-47	Chlorite	No change	H_2O	340	500	1000	S	75	1.0	Chlorite highly dissolved but no alteration

Note re type of experiment: C = compaction; H = hydrostatic; S = shearing.

In these compaction-tests, loose sand-grains were consolidated into true quartzite. The resultant pellet was hard and coherent, and broke across the original sand-grains. In spite of the considerable shortening, however, no preferred orientation was produced in these experiments.

When tested in the shearing apparatus, the mobility was more pronounced. Here the material subject to the shearing stress was so much more soluble that if the experiment was too long continued, the entire sample would dissolve, precipitating on the unstressed walls. When the shearing strain was carried to a high degree, preferred orientation became apparent. Finally, when the material was extremely sheared, the orientation was very nearly perfect, and whole fields of the specimen would assume almost the same orientation, giving the appearance of "super-individuals."

Two modes of orientation were observed, often both in the same specimen, namely, parallel to the shearing motion and normal to it. In the more highly sheared specimens, orientation parallel to the shearing motion predominated.

The shearing fractured the quartz-grains. When shearing was intense, the result resembled a mylonite. A tendency toward the formation of needles was noted, and these needles were most commonly parallel to the "c"-axis. One may well ask whether the preferred orientation was due to a mechanical orientation of these needles, or to the chemical effect of shear. The present experiments do not provide conclusive evidence on this problem, but suggest that both methods produce the same result.

Some experiments were performed on silica glass. No crystallization or devitrification of the glass was observed in the absence of shearing stress. When shearing stress was moderate, as in static compression tests on a solid rod, the result was crystallization into a fine-grained aggregate of cristobalite. Occasional quartz crystals were formed in this solid cylinder, needlelike in appearance, and elongated parallel to the "c"-axis. When the shearing stress was high (strain also high), the common thing was to find the silica completely crystallized to quartz, which was almost perfectly oriented with the "c"-axis parallel to the shearing direction.

Conclusion--Preliminary experiments have been performed in an environment similar to that thought to exist in low-grade metamorphism in nature. The calcite-dolomite reaction occurs readily. Recrystallization of quartz proceeds with ease and at a rate which is accelerated by shearing stress and by increase in temperature up to 600°, in the presence of H_2O under a pressure of 1,000 atmospheres. Olivine alters to serpentine under shearing stress, but not under static pressure.

Aside from these, the changes to be expected in low-grade metamorphism have not been reproduced. It is hoped that the extension of these experiments to higher temperature, longer time, and more complex chemical environments will produce more metamorphic changes and permit their quantitative study, especially with regard to the importance of shear-stress.

Acknowledgments--These experiments were made possible by a project-grant from the Penrose Fund of the Geological Society of America, with which the apparatus was constructed. Milton Heald performed invaluable service in the painstaking measurement of statistical diagrams of quartz aggregates to determine the degree and nature of the induced orientation.

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Cambridge, Massachusetts

SOME QUANTITATIVE EXPERIMENTS ON A FLUID SALT-DOME MODEL AND THEIR GEOLOGICAL IMPLICATIONS

Milton B. Dobrin

(1) Introduction

The tectonics of salt-dome formation has long been a subject for speculation on the part of petroleum geologists and pure geophysicists alike. To the former, the problem has been closely bound with that of locating the oil accumulations which frequently occur in proximity to salt domes. To the latter, it has provided a direct application for theories and experiments relating to the deformation of rocks in general. Conversely, in the development thus far of the various theories upon the mechanics of salt-dome formation, full use has been made of the geologists' field-data as well as the results of experiments in the geophysical laboratories.

All of these theories have had one basic assumption in common; that is, that the salt is of sedimentary origin, having been laid down originally in flat beds and later covered over by other sediments. It is in the dynamics of the upthrust into its present pillar-like configuration that the theories diverge. Many of the mechanisms suggested have involved plastic extrusion of the rock salt upward by compressive forces exerted horizontally upon the salt beds. Others have interpreted the movement as a kind of isostatic compensation having its origin in the density differential between the salt and overlying sediments.

The original proponent of the latter explanation for the upthrust of the salt masses was the chemist Arrhenius [see 1 of "References" at end of paper] who reasoned that the salt, being lighter than the rock-material above it, and hence in an unstable state, should tend to rise independently of any tectonic forces. Later investigators utilized experimental and observational data on the plasticity of rock salt to work out the mechanics of this assumed isostatic adjustment in further detail. Nadai [2] suggested that lateral density-deficiencies in the overburden would give rise to a pressure differential along the salt surface that would cause radial flowage of the salt and consequent lensing of the material over a small area. In 1934, Nettleton [3] integrated and extended these previous hypotheses to formulate a complete theory of salt-dome formation based on the principles of fluid mechanics. The salt and surrounding sediments were both considered to behave over geologic time as highly viscous liquids; and no other force than the differential pressure set up by the density-contrast of the two fluids was required to explain the upthrust. This theory was the first to explain adequately the formation of the rim synclines which had been observed in the sedimentary formations surrounding many of the domes in northeast Texas. On the basis of it, Ritz [4] subsequently demonstrated that structural anomalies discovered by drilling around certain domes in the Gulf Coast were probably unrecognized rim synclines.

To illustrate the theory qualitatively, Nettleton constructed dynamic models in which the salt and sediments were each represented by viscous liquids. In each model, the two fluids were immiscible and the one corresponding to the salt was of lesser density than that corresponding to the overburden. The most realistic model-domes were observed to form when the overburden was simulated by thick corn-syrup and the salt by asphalt-base crude oil.

In 1937, Hubbert [5] published a quantitative study of geologic models, utilizing the principles of dimensional analysis and of dynamic similarity. He considered the Nettleton salt-dome model in the light of these principles and worked out the simple relationships that would have to obtain between the ratios of viscosity, density, length, and time in the model and in the original in order for the model to give a valid representation of the situation in nature. He suggested some quantitative experiments upon the model that might yield information of geologic significance.

(2) Object of present experiments

The work to be reported upon here was undertaken with two purposes in mind. The first was to subject the fluid theory of salt-dome formation to a quantitative test. The second was to study, from observations upon model domes, the kinematics and to postulate the dynamics of salt-dome formation in nature. The validity of any such corollaries would be dependent, of course, upon a favorable outcome of the test constituting the first objective.

In his analysis of the Nettleton fluid model Hubbert showed that the following equation expressed the relationships that must be maintained for dynamic similarity between the model and its original

$$\psi = \delta \lambda \tau \qquad (1)$$

where ψ is the ratio between the viscosities in the model and in the prototype, δ the ratio of densities, λ the ratio between a characteristic length in the model and the corresponding length in the protytype, and τ the ratio of the time required for the model dome to rise to a given configuration to that required for a dome in nature to rise to a geometrically similar configuration.

If one could show by an appropriate model-experiment that the condition expressed in equation (1) is satisfied, then strong support should be afforded to the conception that rocks deform under long-continued stress in the same manner as viscous fluids. The mechanism by which rocks "flow" or "creep" under differential pressure has been the subject of a considerable amount of recent investigation, both theoretical and experimental, by Goranson [6] and Griggs [7]. Considering the problem as one in thermodynamics, Goranson developed the hypothesis that plastic flow in solids takes place through a cycle of phase-changes, either by melting and recrystallization or by solution and reprecipitation. The relationship between stress and rate of shear which in a fluid is known as viscosity becomes, in his interpretation, a function of the "activation-energy" of the solid, which is in turn dependent upon the differential pressure or tension giving rise to the flow. Griggs' experiments on the creep of rocks in the laboratory have confirmed the theoretical relations thus deduced. They have demonstrated, for example, that a threefold increase in compressive stress gives rise to a hundredfold decrease in the equivalent viscosity of wet alabaster.

Since the viscosity-coefficient in a non-plastic liquid is independent of the stress, some question might arise as to the propriety of setting up a model-ratio of viscosity in connection with the present experiments. One justification is embodied in the time-element involved. It is well known that deformations in the Earth's crustal rocks that have required tens of millions of years to take place cannot be reproduced in the laboratory under equivalent stresses and confining pressures. Moreover, the macroscopic scale upon which salt-dome formation takes place in nature is such that we can consider the salt and sediments to have average effective viscosities which could be reasonably compared with the viscosities of the fluids in the model. Finally, there is evidence, largely to be found in the lines of flow observed where salt domes have been mined, that the domes have risen in static equilibrium between the buoyant forces acting upward and the form resistance of the sediments opposing the upthrust. Under these circumstances, one would expect a constant differential stress within the salt and hence a relatively constant effective viscosity which would be comparable with that in the model dome.

(3) Setting up of model-ratios

In order to establish the model-ratios of length, time, density, and viscosity, it is necessary to make a critical study of the conclusions that various geologists have reached after investigations of actual salt domes. Since few domes rise close enough to the surface for direct field-studies of their properties, the major part of the information thus far accumulated has been derived from drilling logs and geophysical data. For this reason, much of our knowledge of salt domes rests on a somewhat speculative basis. Moreover, salt masses in different parts of the world seem to vary greatly in their properties and morphology. In the Gulf Coast, the salt has pushed its way upward almost to the surface in approximately the form of circular cylinders rounded off at the top. In Germany, the masses seem to be found in all shapes and sizes, ranging from elongated anticlines to symmetrical domes. In Rumania, the domes have sharp, angular structures which make them appear to be the results of overthrusting. The Persian domes have in many cases pierced the surface of the ground and some of them now rise as much as 4,000 feet above the surrounding country. In German and Rumanian salt basins, the salt flow has undoubtedly been modified by associated tectonic movements which exclude them from consideration in the present study. However, since the domes in Persia and along the Gulf Coast seem to correspond in geometrical configuration to the symmetrical domes obtained in the model experiments and since a large body of observational data has been accumulated on the domes of both regions, these will be considered as the prototypes in setting up the various model ratios.

(a) __Length__--The most appropriate characteristic distance to choose in setting up a model ratio for length should be the height of the dome. It is generally agreed that the Gulf Coast and Persian domes were both formed from salt beds now buried under about 20,000 feet of sedimentary rock. Since the tops of the salt domes extend almost to the surface in one region and often project somewhat above it in the other, we can choose 20,000 feet as the height of a characteristic dome in either province. The diameters of these structures vary considerably, but the average is in the neighborhood of two miles. A model-dome whose diameter is roughly one-half its height would thus be geometrically similar to its prototype. In the models employed for the present experiments, this condition obtained when the dome was 12 cm high. Hence the model-ratio of length, λ, becomes 12 cm/20,000 ft, or 2×10^{-5}.

(b) __Time__--More uncertain than the size and shape of a typical salt dome is the time that was required for it to rise from the mother salt layer to its present configuration. However, in both of the salt-dome provinces under consideration there is reasonably good evidence as to the geologic period in which the salt was initially laid down, so that we are fairly certain of an upper limit to the time it took the plugs to rise in these regions.

It has been well established by Lees [8] and Richardson [9] that the older and more prolific of the two sedimentary salt series, the Hormuz, in Persia is early Cambrian. In recent discussions of the problem, Lees [10] and Harrison [11] give evidence that the salt began its upward movement in the upper Cretaceous and penetrated the surface of the ground at various periods ranging from the Miocene to post-Pliocene. Daly [12] has prepared a tabulation of the geologic time-scale, based on Schuchert's estimates and radioactivity-data, and from it one finds that the interval from Upper Cretaceous to early Tertiary was 100 million years. This, roughly, should be the total time required for a typical Persian dome to form.

In the Gulf Coast, there is no general agreement among geologists as to the age of the mother salt beds, although several lines of inference lead to the tentative conclusion that it is Permian. Barton [13] quotes definite evidence that the salt must be older than uppermost Upper Cretaceous and mentions the fact that fossil algae have been found in the salt of the Markham Dome in Texas that have been claimed to be identical with algae found in salt known to be Permian. In nothern Louisiana and northeastern Texas wells have recently been drilled in which salt has actually been reached at depths of 8,000 to 11,000 feet. The age of the salt has been variously called Triassic to Permian. Taking the regional dip of the area into consideration, this salt bed could correlate with the salt formations postulated to be 20,000, or more, feet deep along the Gulf Coast proper. In an attempt to deduce the time during which actual rise took place, Barton calls attention to the thinning of the Wilcox (early Eocene) beds around the Clay Creek dome as evidence that the upthrust was going on at that time. Since the dome-formation must have been well under way to produce such an effect at this depth, one must infer some pre-Mesozoic time for the inception of the upthrust. Now several thousand feet of overburden are necessary to compact the sediments directly overlying the salt to the extent that their density would be greater than that of the salt, and therefore the upward motion of the salt could be isostatically motivated. It is not likely then that dome-formation would have begun before Travis Peak time (basal lower Cretaceous), when, according to northern Louisiana well-logs, there were 3,000 feet of sediments over the salt. If the salt is considered then to have risen from the Cretaceous to Recent times (as is indicated by mounds in post-Pleistocene surface-formations above several Gulf Coast domes) Daly's tabulation sets the time available for Gulf Coast dome-formation at 120,000,000 years.

Comparing this with the 100,000,000-year period deduced for the Persian salt domes, one feels justification for putting the time for the upthrust of a typical salt dome at 10^8 years when setting up the model-ratio of time, τ, for the purposes of the present experiment. The ratio will then be $(t_m/3.15 \times 10^{15})$, where t_m is the time in seconds required for a model-dome to reach the height of 12 cm.

(c) Density--The simplest of the model-ratios to set up is that of density. Nettleton has plotted a curve of sediment-density versus depth based both on measurements and theoretical considerations. From it, one can postulate the average density of the sediments as 2.4 g/cm^3. The rock-salt has a uniform density of 2.2 g/cm^3. The density-contrast is thus 0.2 g/cm^3. In the two models that were experimented upon, one had a contrast of 0.485 g/cm^3 between the material representing the sediments and that representing the salt; the other had a contrast of 0.569. Since it is the density-contrast rather than the density itself which determines the buoyant force giving rise to the upthrust, it is necessary to consider the model-ratio of density as the ratio of the contrasts, which for the first model will be 2.4, for the second, 2.8.

(d) Viscosity--The model-ratio for viscosity is difficult to establish with certainty, mainly because the relative viscosities of the sediments and salt in nature are not very well known. In the performance of these experiments, various ratios between the viscosity of the material representing the salt and of that representing the overburden were tried and it was found that the rate of rise was surprisingly little affected by the viscosity of the salt material as long as that of the sediment-material was kept constant. That this should be the case is suggested by the results of Hadamard's [14] theoretical work on the rate of fall of a liquid drop through another liquid. He showed that a liquid drop with a viscosity equal to zero will fall through another liquid two-thirds as fast as a solid sphere of the same diameter having infinite viscosity and obeying Stokes' law. This shows that the rate of fall is not very sensitive to the viscosity of the liquid in the sphere. While the two cases are not exactly analogous, there is sufficient correspondence in their dynamics to suggest that it is the viscosity of the sedimentary overburden rather than the plasticity of the salt that is the principal factor governing the rate of rise. Further evidence for this conclusion is given by the present experimental results, to be discussed further on.

The viscosity of the Earth's crustal and sub-crustal rocks has been investigated both by direct and indirect methods. The direct methods have involved actual laboratory measurement of the "creep"-rate of rocks under stress. Weinberg [15], measuring torsional deformation over hundreds of days, obtained a value of 10^{18} poises for the viscosity of rock-salt at 18° C and one of 10^{16} poises for Iceland spar at the same temperature. Griggs more recently has carried on a series of experiments upon the deformation with time of rocks loaded below their normal breaking-strength and has in many cases been able to calculate an equivalent viscosity for the portion of the flow which he designates as "pseudo-viscous." He observed that when the material under investigation was in solution under conditions favoring recrystallization the viscosity was much less than when the material was dry. Whereas the equivalent viscosity of alabaster in water was found to be of the order of 10^{16} poises, the same material in the dry state would have to have had a viscosity greater than 5×10^{18} poises, the limit of resolution of the apparatus employed. Similarly, it was shown that Solenhofen limestone when dry must have a minimum viscosity of about 2.2×10^{22} poises.

The viscosity of the sub-crustal medium whose flow governs the isostatic adjustment of the Earth's crust has been calculated by Vening Meinesz and independently by Haskell from evidence upon the amount of surface-uplift that has been observed in Scandinavia after the withdrawal of Pleistocene glaciation. Their methods and results are discussed by Gutenberg [16], who points out that both values agree to within one order of magnitude, namely, 10^{22} poises. That the crust itself should be more viscous than its substratum is, according to Griggs, in agreement with geologic evidence that the crust will not flow in response to small stresses even when applied over long periods.

The entire problem is complicated by the fact that laboratory experiments cannot supply the element of time that enters into salt-dome formation in nature; also, there remains some uncertainty whether small test-specimens of a material will have the same physical properties as a macroscopic aggregation of the same material on a scale that must be measured in miles.

Since the viscosity of the salt and sediments is the least certain of any of the quantities involved in the present model experiment, we shall leave it as the dependent variable to be computed in terms of the experimental data and the other model ratios. The test of the theory illustrated by the model would depend on how reasonable is the equivalent viscosity so calculated in the light of the above considerations.

(4) Experimental procedure

The principal objective of the experimental procedure was to measure the height-time relationships of a number of fluid model domes having as wide a range of viscosities as possible. The variation in viscosity for each model was obtained by changing the temperature of the apparatus. The viscosities of all the materials used to represent the salt and sediments were determined as functions of the temperature over the range 95° to 30° F. The temperature for each set-up at which rise-rate measurements were made was kept constant by suitable controls.

(a) Construction of models--The two models upon which observations were made correspond very closely in principle to some which Nettleton described in his original paper. In one, the overburden was simulated by Karo corn-syrup boiled down until its boiling point was raised from 105° to 111° C, and its specific gravity raised to 1.455 at room-temperature. The salt was represented by a heavy asphaltic residuum oil (the portion of the crude oil that remains when all volatile constituents are distilled off in the refining process), the specific gravity of which was 0.970. In the other model, the sediments were represented by the same syrup that was used in the first, but the salt was simulated by a light motor-oil stiffened by a 20 per cent admixture of "Paraflow" wax, the resultant specific gravity being 0.886. In each model the layer of material representing the salt was about 3/4 inch thick.

The container for each model was a cylindrical battery jar seven inches in diameter and nine inches high, the open end of which was sealed by a flexible thiokol diaphragm, held fast to the periphery of the jar by an annular steel ring which was clamped by eight bars to a circular steel disk below the closed end. By loosening the clamps it was possible to remove the rubber diaphragm and change the liquids inside the jar. When the model was inverted so that the oil would be under the denser syrup, the formation of the dome was initiated in the center of the cylinder by allowing the diaphragm, which would then be at the bottom, to rest upon a correctly placed hemispherical metal boss. Figure 1 shows two pictures of the model in which the salt was simulated by the residuum oil. One of these shows a dome in the process of formation. The other shows the details of the construction of the model.

(b) System for controlling temperatures--Each series of measurements upon the model-domes was carried on with the system in thermal equilibrium at a predetermined temperature. During these runs, as well as for the two days preceding each one, the model was kept inside of a large insulated box in an air-bath whose temperature was controlled by low-power heaters turned on and off by a mercury thermostat operating a relay. With the help of an electric fan, the temperature was maintained constant within 0.1° C. When it was desired to maintain the model at a temperature lower than normal room-temperature, the apparatus was moved to a cold room in which the temperature was adjusted to be somewhat lower than that at which the model was to operate. In order that the temperature would not be altered during a rate-of-rise measurement, readings were taken through windows in the constant-temperature box. The attainment of thermal equilibrium

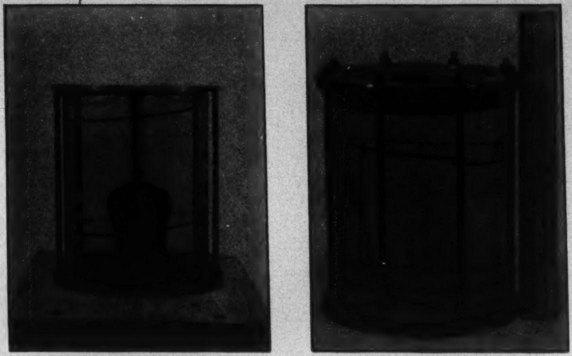


Fig. 1-A Fig. 1-B

Fig. 1--Two views of salt-dome model apparatus: A, model dome in process of formation; B, details of model's construction

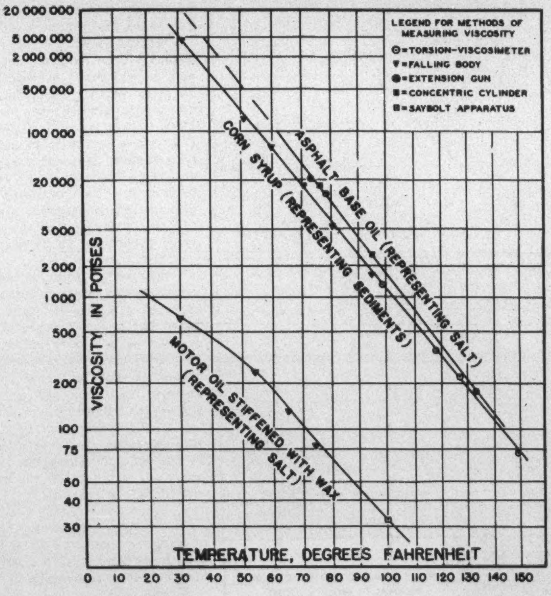


Fig. 2--Viscosity-temperature relationships for fluids used in salt-dome models based on A.S.T.M. chart (D341-37T)

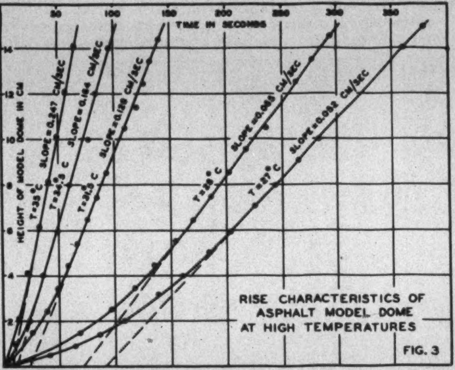


FIG. 3

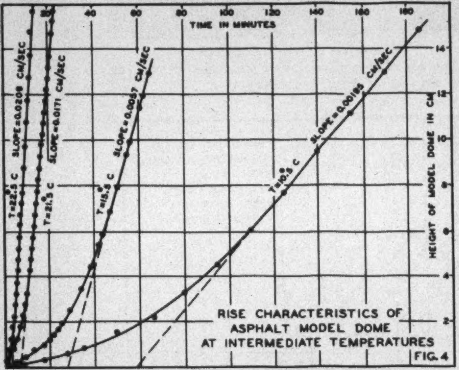


FIG. 4

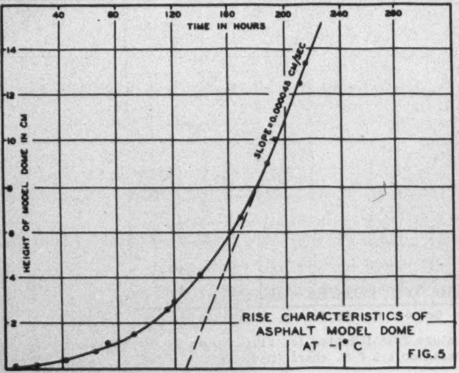


FIG. 5

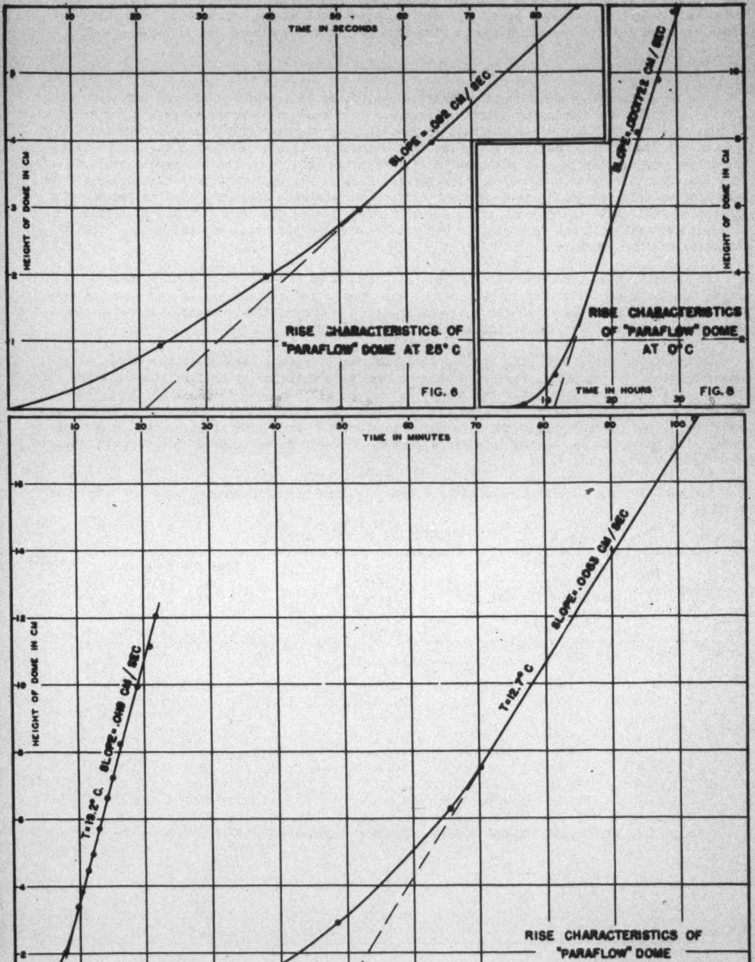
Figs. 3, 4, 5--Height-time curves of asphalt domes

within the model was tested by making successive determinations until the rate was not observed to change with time.

(c) Viscosity-measurements--Since the viscosities of the three materials employed in the two models varied by a factor of 10^5 over the temperature-range at which rise-measurements were made, it was necessary to use several different methods of measuring viscosity to obtain a complete curve of viscosity versus temperature for each fluid. Measurements on the syrup at higher temperatures using the MacMichael torsional viscosimeter and measurements on the heavy oil using a pressure extrusion-gun were made by members of the Chemistry Division of the Gulf Research and Development Company. Measurements on the heavy oil at two temperatures by determining relative motion of concentric cylinders with the liquid in between were made by the tar-products laboratory of Mellon Institute. Further determinations upon the transparent syrup and the "Paraflow" mixture were made by the writer using the falling-ball method. This involved the measurement of the rates at which steel balls of various sizes fell through the liquid media at the various temperatures under consideration. The viscosities were calculated from Stokes' law, modified, as suggested by Bacon [17], by correction-factors for the dimensions of the cylindrical containers. Tests made for plasticity on the heavy oil and syrup turned out to be negative.

Figure 2 shows the composite viscosity-temperature curves determined by plotting the data for the three fluids as obtained by the various methods on a standard A.S.T.M. chart. This chart is set up on the empirical principle that for most liquids a plot of the log log of the viscosity against the log of the temperature will give a straight line. This is observed to be the case for the syrup and the heavy oil but not for the motor-oil and "Paraflow" mixture.

(d) Method of measuring rate of rise--The height of the model-dome was measured as a function of time at each temperature by follow-



Figs. 6, 7, 8--Height-time curves for "Paraflow" domes ing the top surface of the dome with the telescope of a vertical cathetometer. The intervals at which height-time values were noted depended upon the speed of dome-formation. The range of times required for the various domes to rise extended from one minute to ten days.

(5) Experimental results

The data thus obtained upon the heights of the domes as a function of time and temperature are plotted in the accompanying charts. Figures 3 to 5 show these characteristics for the series of runs upon the model in which the salt is simulated by the highly viscous residuum oil. Figures 6 to 8 are for the model in which the less viscous motor-oil represents the salt. All of the curves are similar in form although it will be noted that those for the second model do not show the dome to rise as high as do those for the first. The explanation is that domes of the less viscous material would begin to pinch off at the base when about six cm high and shortly thereafter would lose their domal shape altogether and assume the form of floating ellipsoids. It is of interest that the rate of rise before the pinching off began was the same as that of the globule after separation.

An inspection of the curves indicates that the rate of rise for each dome increases rapidly during the early states of its formation; but when the height reaches six or seven cm the rate becomes constant and remains so for the remainder of the upward flow. The slope of the linear portion has been measured and is indicated on each curve.

To determine the actual rate of rise as a function of height throughout the course of the dome-formation, the slopes of the height-time curves were measured at uniform intervals and were plotted as a function of height. The resultant curves, although fairly smooth, did not seem to exhibit any recognizable form; but when the data were replotted so that the scale of height was logarithmic, the curves assumed the form shown in Figure 9, each consisting of two linear segments, with the upper one having less slope than the lower. No explanation for this characteristic has yet been found.

The most pertinent quantities derivable directly from the experimental data are tabulated in Table 1.

Table 1--Properties of model domes

Run No.	Temperature, °C	Viscosity of syrup, poises	Viscosity of oil, poises	Slope of linear portion of curve, cm/sec	Reciprocal slope, sec/cm	Time for dome to rise 12 cm, sec	Ratio - viscosity of syrup time to rise 12 cm
			Asphalt model				
1	35.0	1800	2700	0.247	4.05	57	31.6
2	34.5	2000	3000	0.164	6.10	85	23.7
3	31.0	3400	5000	0.128	7.82	122	36.0
4	28.0	5000	8700	0.065	15.4	260±	19.2
5	27.0	6300	10,000	0.052	19.25	312	20.1
6	22.5	14,000	25,000	0.0209	47.9	660	21.2
7	21.5	17,000	30,000	0.0171	58.5	1115	15.2
8	15.5	59,000	130,000	0.0057	176	3735	15.8
9	10.5	190,000	520,000	0.00195	511	9720	19.5
10	-1.0	4,500,000	25,000,000(?)	0.000045	22,000	743,000	7.8
			"Paraflow" model				
1	25.0	17,000	77	0.092	10.87	149	114
2	19.2	28,000	130	0.0119	84	1300	21.4
3	12.7	120,000	230	0.0053	188.5	5060	23.7
4	0	4,500,000	600	0.000172	5820	109,500	41

(6) Application of model-theory to data: Test of fluid-salt-dome theory

In applying the present data to equation (1), one can set up the equation in terms of the constants previously discussed and of the experimentally determined quantities as in equation (2).

$$(\eta_m/\eta_p) = 2.4 \times 2 \times 10^{-5} \, x t_m \text{ (in sec)}/3.15 \times 10^{15} \qquad (2)$$

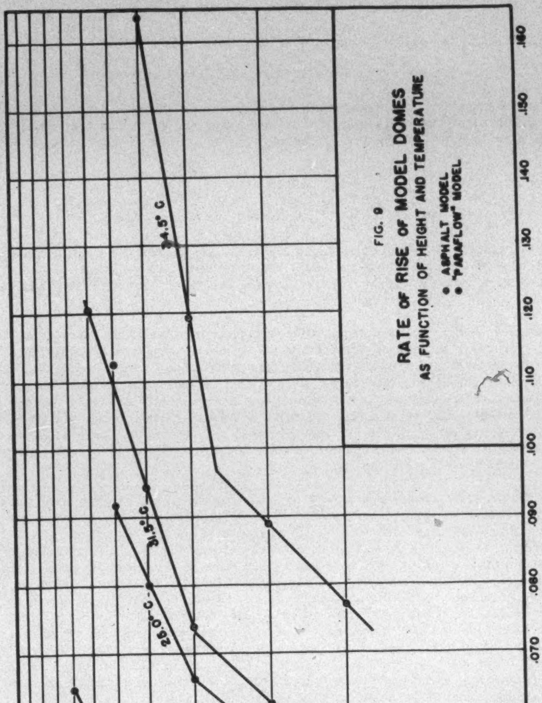


FIG. 9

RATE OF RISE OF MODEL DOMES
AS FUNCTION OF HEIGHT AND TEMPERATURE

for the model in which the salt is simulated by the residuum oil and

$$(\eta_m/\eta_p) = 2.8 \times 2 \times 10^{-5}\, x t_m \text{ (in sec)}/3.15 \times 10^{15} \tag{3}$$

where η_m is the viscosity of the model-material representing the sedimentary overburden, η_p is the average viscosity of the sedimentary rocks in nature, and t_m is the time required for a model-dome to rise 12 cm. Solving for η_p, we get

$$\eta_p = 0.65 \times 10^{20}\, \eta_m/t_m \text{ for the first model} \tag{4}$$

and

$$\eta_p = 0.55 \times 10^{20}\, \eta_m/t_m \text{ for the second model} \tag{5}$$

The ratios (η_m/t_m), as computed in Table 1 average 21 ± 4 for the model containing the heavy oil and 50 ± 20 (or neglecting the least reliable value, 29 ± 6) for the one with the light oil. The first ratio gives us a value of $1.4 \pm 0.3 \times 10^{21}$ poises for η_p and the second gives one of $2.7 \pm 1.1 \times 10^{21}$ poises.

This average value is just one order of magnitude lower than those computed by Haskell and Vening Meinesz for the viscosity of the portion of the Earth's upper mantle giving rise to crustal movement. It is several orders of magnitude higher than the viscosities, as experimentally determined, of rocks saturated with fluid. Since there is geological evidence that the body of the Earth's crustal rocks--presumably the harder and deeper strata--are more viscous than the material in the sub-stratum, it would appear that the value of the average viscosity of the upper crust as here derived represents a reasonable mean between the viscosities of the more rigid, less-soluble sedimentary rocks and those of the saturated, more-plastic layers through both of which the salt would have to push its way.

Since so little difference was observed in the times and rates of rise when the material representing the salt was replaced by another having 1/10,000th its viscosity, it is not possible, from the results of these experiments, to suggest a value for the viscosity of rock salt in nature. That the resistance of rock salt to plastic deformation should decrease with increased depth of burial is an assumption that many geologists seem to have made in their discussions of salt-dome tectonics. However, none of them has pointed to any experimental evidence that the viscosity decreases under increasing ambient pressure. About the only information on this phase of the subject available in the literature is in observations noted by Lees [10] that the deeper galleries in certain Alsatian and German salt mines show much more tendency to close in by gradual flow of the salt than do higher galleries supporting less overburden. This evidence is not conclusive, since it does not show whether it is the differential or ambient pressure that causes the increased plasticity. Some more direct experimental work on the strength of rock salt under hydrostatic pressure would be of value in this connection.

Considering the limits of the error inherent in the assumption of numerical values for the characteristics of actual salt domes, it is believed that the results here obtained support, within these limits, the validity of the fluid mechanical theory of salt-dome formation.

(7) Hydromechanical analysis of data

Like most problems in the hydrodynamics of viscous fluids, the case of dome-formation in a fluid model of the type under consideration is much too complicated to be worked out rigorously by conventional mathematical methods. While the motion of a solid or irregular shape through a viscous liquid constitutes a difficult enough problem, the motion of one highly viscous liquid through another, except for such a simple case as that of a spherical drop, has never been solved at all, to the writer's knowledge. The method of analysis that is used here is a common one for studying many geophysical problems. It involves the setting up of equations for an oversimplified and idealized case of the general problem and comparing their solutions with observational data. Any divergence between the two may suggest revisions in the original simplifying assumptions and help clarify the physical situation.

Consequently, in setting up the problem of determining the height of a fluid model dome as a function of time, the following assumptions are made: (1) The model-dome forms in the center of a large cylindrical box; (2) it is cylindrical in form and has a flat top; (3) the dome material is considered to be a solid of variable height pushing its way upward through a viscous liquid of greater density, in this case the syrup; and (4) boundary-effects, particularly those which cause "mushrooming" of the dome at the top of its trajectory, are neglected.

The symbols to be used in this analysis are defined as follows: z = height of top of dome above surface of the layer from which it originates; t = time from initiation of upthrust; $v = dz/dt$; R = radius of dome (assumed constant); w = characteristic distance expressing proportionality between velocity and velocity-gradient; ρ_1 = density of syrup; ρ_2 = density of dome-material; $\rho_d = \rho_1 - \rho_2$ = differential density; η_1 = viscosity of syrup; ψ = Newtonian form-resistance coefficient; g = acceleration of gravity.

Now when the dome is at any height z, there will be three forces acting:

(1) The buoyant force, acting upward

$$F_b = \Delta p A = \rho_d \pi R^2 g z \tag{6}$$

(2) The viscous drag along the side of the cylinder, acting downward

$$F_v = \eta_1 2\pi R z \ [(dz/dt) - 0]/w = (2\pi R \eta_1/w)\, z\, (dz/dt) \tag{7}$$

(3) The force required to push aside the liquid displaced by the rise, which also opposes the upward motion

$$F_f = (\psi \pi R^2 \rho_1/2)\, (dz/dt)^2 \tag{8}$$

Assuming the inertial forces to be negligible so that the algebraic sum of these three forces is zero, and calling

$$K_1 = \rho_d g R \qquad K_2 = 2\eta_1/w \qquad K_3 = \psi R \rho_1/2$$

one obtains the differential equation

$$(dz/dt)^2 + (K_2/K_3)\, z\, (dz/dt) - (K_1/K_3)\, z = 0 \tag{9}$$

which can also be expressed in the form

$$v = (K_2/2K_3)\, [- z \pm \sqrt{z^2 + (4K_1K_3/K_2^2)z}] \tag{9a}$$

A solution for $t(v)$ may be obtained from the relation (the writer is indebted to L. W. Gardner for suggesting this simplified mode of representation)

$$t = \int (1/v)\, (dz/dv)\, dv + \text{constant} \tag{10}$$

Taking (dz/dv) as a function of v from equation (9a) and accounting for the initial condition that $v = 0$ when $t = 0$, this becomes

$$t = (K_3/K_2)\, \ell n \ 1/[1 - (K_2/K_1)\, v] + (-K_2/K_1)\, v/[1 - (K_2/K_1)\, v] \tag{11}$$

Equations (9a) and (11) together furnish a relationship between z and t. This relationship is shown by the dimensionless curve of Figure 10, the constants being incorporated in the coordinates.

Equation (9a) may be expanded into

$$v = (K_1/K_2) - (K_1^2K_3/K_2^2)\, (1/z) + \ldots \tag{9b}$$

From this, it is evident that as z becomes large, v approaches the limiting value (K_1/K_2), which ratio equals $(Rw/2)\, (\rho_d g/\eta_1)$, indicating that at equilibrium the slope of the linear portion of the curve should be directly proportional to the density-contrast and inversely proportional to the viscosity of the syrup.

Comparing the theoretical curve with the empirical height-time curves, one sees many points of similarity. The general form of the beginning portion is concave upward in both cases, and both approach linearity subsequently. To test out the application of equation (9a), the viscosities of the syrup for the various experimental runs were plotted against the reciprocal slopes of the linear portions of each curve as shown in Figure 11. The resulting curve is smooth and approaches linearity. The departure from linearity can possibly be explained by the fact that the effective viscosity would be expected to depend to some extent upon the viscosity of the dome-material and hence not entirely upon that of the syrup. The problem of expressing this effective viscosity analytically in terms of the two viscosities involved appears to be exceedingly difficult. Another source of discrepancy might be that w doesnot remain constant for different viscosities.

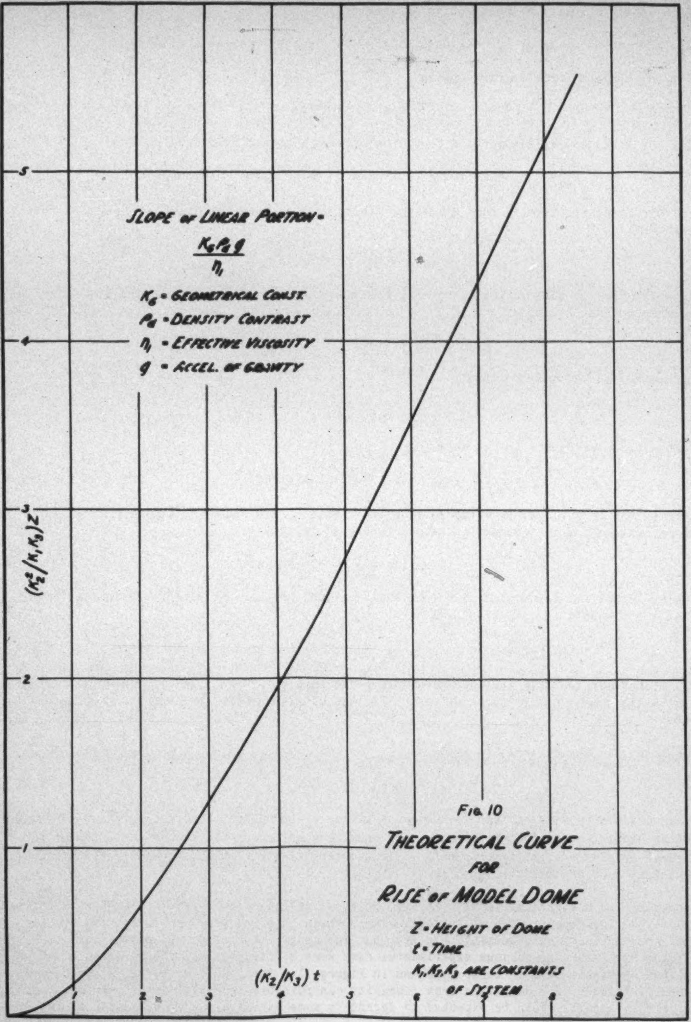


FIG. 10

THEORETICAL CURVE FOR RISE OF MODEL DOME

Any divergence between the theoretical curve and experimental curves can be explained qualitatively if it is remembered that the theoretical dome was assumed to push its way up effectively as a solid whereas in actuality the dome-material had to overcome a great deal of internal friction in its transition from a flat layer to a quasi-cylindrical mound standing above that layer.

It is in this connection that the curves of Figure 9, showing the rate of rise before the rate becomes constant, should be of especial interest. According to them, the velocity is a logarithmic function of the height. The separation of each curve into two linear segments of different slopes would suggest that there are two stages in the initial part of the process. Since the stress giving rise to the flow is proportional to the height of the dome, it is likely that the mechanism of dome-initiation could be deduced from a further study of these curves. The slopes of corresponding linear segments were plotted on log-log paper as a function of the viscosity of the material simulating the dome, and the relation appeared to be linear within the limits of error.

After a constant rate of rise is reached a flow-pattern is established representing an equilibrium between the buoyant and viscous forces. Some question arose whether this linear rise takes place only after flow of additional material into the dome has been cut off by the peripheral sink in the manner postulated by Nettleton. Measurements on some photographs showing successive stages in the formation of model-domes indicated that material continues to flow into the dome from the region outside the peripheral sink all during the stage of constant rise. This would suggest that the cross-sectional area through which flow takes place around the base of the dome remains constant.

(8) Geological implications of results

From observations upon a dynamically similar model it should be possible to derive some tentative conclusions regarding the dynamics of upthrust of salt domes in nature. If the dimensional tests demonstrated earlier in this paper are accepted as being indicative that dynamic similarity exists within natural limitations, then the following corollaries can be drawn regarding the mechanics of salt-dome formation:

(a) Over long periods of time salt domes form by a process of flow comparable to that of highly viscous liquids in the manner suggested by Arrhenius, Nadai, and in more detail, by Nettleton.

(b) The governing factor in determining the characteristics of salt-dome formation is not so much the viscosity or plasticity of the rock salt itself as it is the viscosity or plasticity of the sedimentary overburden. This might explain why salt domes are not found in many regions, such as West Texas and Michigan, where thick salt deposits are known to be buried. In such cases the competency of the overlying rocks might not permit the initiation of the upthrust.

(c) The initial stages of dome-formation are very slow, but as the rise continues, the upward buoyant forces gradually overcome the internal resistance to deformation associated with

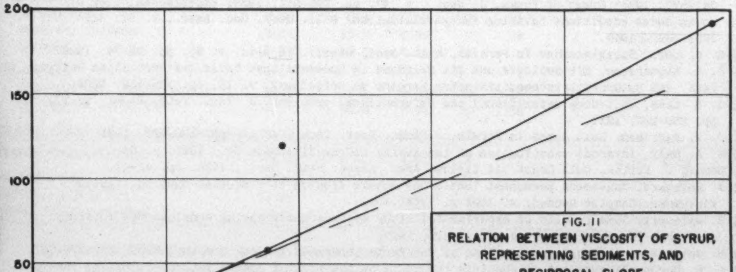


FIG. 11
RELATION BETWEEN VISCOSITY OF SYRUP REPRESENTING SEDIMENTS, AND RECIPROCAL SLOPE OF HEIGHT-TIME CURVE

the plasticity of the salt and overburden, so that the process increases in speed until the domal shape is well established. This part of the rise seems to take place in two separate stages, the natures of which are not clear. The more rigid the rocks the greater the relative time required for established flow to begin.

(d) Once the rise of the dome is well begun, the dome's further upthrust takes place at a constant rate with an established flow-pattern indicating equilibrium between the gravitational and resistive forces. One may infer that the upper half of an average dome's rise takes place under these equilibrium-conditions. Of course, variations in the rigidity and competency of the overlying beds would affect the rate of rise somewhat, but the average resistance, distributed over the area of the dome, would probably not vary by much.

(e) When the thickness of the mother salt layer is around ten per cent of the height of the dome, the flow of salt continues into the dome from the region outside the peripheral sink, indicating that cut-off by the sink has not yet taken place.

(f) An average effective viscosity of the order of 10^{21} poises is indicated for the rocks constituting the uppermost four miles of the Earth's crust in the two salt-dome areas under consideration, Persia and the Gulf Coast.

(9) Acknowledgments

The writer is especially indebted to Dr. L. L. Nettleton for suggesting this problem, for his helpful supervision of the experimental work, and for many valuable discussions. He also wishes to express his appreciation to Anthony Carnvale, Malcolm Gay, and Dr. Charles Montgomery for the loan of apparatus; to A. R. Rescorla and W. A. Lutz, of this Company, and to Dr. W. F. Fair, of the Mellon Institute, for making viscosity-determinations; to J. L. Scott and J. B. Brooks for tracing the Figures; to W. E. Marshall for assistance of various sorts; and to L. W. Gardner, P. G. Exline, and C. H. Dresbach for helpful discussions. He acknowledges, finally, his indebtedness to Dr. Paul D. Foote and Dr. E. A. Eckhardt for authorizing work on this project and for permitting the presentation and publication of the present paper.

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THE EFFECTS OF SIMPLE COMPRESSION AND WETTING ON THE THERMAL CONDUCTIVITY OF ROCKS

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Measured thermal gradients in the Earth run from about 6° per km to 150° per km. Some of the differences may be due to differences in the rate at which heat is flowing toward the surface, but many of them result, doubtless, from differences in conductivity of the rocks through which the heat flows. Out of hundreds of gradient-measurements, only about a dozen have been correlated with conductivity, and it is significant that in these cases the values obtained for the rate of heat-flow differ from their mean value by only about 25 per cent, although the gradients themselves vary by a factor of four or five.

Some of the other gradient-measurements might be used if we had any way of estimating the conductivities of the various kinds of rock in terms of their petrography or mineral composition, their porosity, and perhaps other factors. Such a systematic study has been found possible for the compact fresh igneous rocks whose conductivities can now be estimated to within five or ten per cent when the composition is known. Most of the measurements of gradient have been made in sedimentary rocks--shales, sandstones, limestones. The work which I am about to describe is a preliminary attempt by Dr. Birch and myself to discover what are the principal factors affecting the conductivity of such materials. We naturally suppose that for a given mineral composition, which determines the intrinsic conductivity of the rock in terms of those of the minerals, such factors as porosity and permeating fluid would be most important. The porosity can be changed by stress, and air can be replaced by water. So the effects of compression and of soaking in water seem to be the first ones to study.

The essential part of our apparatus is the central, vertical column of a press. It consists of a series of five solid cylinders, 1.5 inches in diameter, one above the other--three of steel, separated by two flat circular discs, 0.25 inch high, of the rock to be studied. The rock may thus be subjected to simple compression, which seems better adapted to our purpose than hydrostatic pressure, since it should tend to close up those cracks or pores which lie in horizontal planes and which are thus most effective in restricting the vertical flow of heat. The middle steel cylinder serves as a source of the heat which flows through the specimens; it is heated electrically. The temperature-drops across the specimens were measured by thermocouples set into the steel pieces very close to the rock-surfaces. The flat faces of both rock and steel were

Table 1

Rock (1)	Bulk-density (2)	Porosity (3)	K_o (4)	$\left(\frac{\Delta K_p}{K_o}\right)$ (5)	$\left(\frac{\Delta K_w}{K_o}\right)$ (6)	$\left(\frac{\Delta K_{wp}}{K_o}\right)$ (7)	K_m (8)	K_h (9)
		pct		pct	pct	pct		
Marble, Danby, Vermont	2.67	1.1	5.80	13	11	2	6.62	....
Limestone								
Solenhofen	2.60	3.4	5.03	13	23	..	6.19	6.25
Bedford, Indiana	2.31	13.2	4.40	7	14	1	5.06	....
Bermuda	1.55	43.0	2.11	22	..	..	2.57	....
Sandstone								
Doubling Gap, Pennsylvania	2.64	0.5	9.20	18	13	4	10.9	....
Owl Canyon, Colorado	2.17	22.0	4.43	30	36	6	6.3	....
Shale, Sunderland, Massachusetts	2.67	....	3.87	10	..	..	4.25	....
Slate, Pennsylvania	2.76	....	4.32	4	..	..	4.50	4.42
Anorthosite	2.72	....	4.13	1	..	..	4.17	4.12
Gabbro, Wisconsin	2.87	....	4.51	2	..	..	4.60	4.67
Mica, single crystal	2.83	....	1.67	4	..	..	1.74	....

K_o = conductivity of dry, uncompressed rock at 45°C, in 10^{-3} (cal/cm.sec.°C)

ΔK_w = increase of conductivity after soaking in water

ΔK_p = reversible increase of conductivity of dry rock on compressing to 10,000 lb/in^2

ΔK_{wp} = reversible increase of conductivity of wet rock on compressing to 10,000 lb/in^2

K_m = maximum observed conductivity for compressed, wetted rock

K_h = conductivity previously measured in an atmosphere of helium ground and lapped, and good thermal contact was assured by using vaseline or glycerine. Precautions were taken to minimize lateral heat-losses, and the unavoidable losses were measured by using specimens of pyrex glass of known conductivity. The results are shown in Table 1.

Column (5) shows that compression produces only small effects on the slate and the igneous rocks; they were completely reversible. This was to be expected since their porosity is practically zero.

For the sedimentary rocks of low porosity, marble and Doubling Gap sandstone, the effect of compression alone [Column (5)] is about the same as the combined effects of pressure and wetting [Column (6) + Column (7)]. For the more porous rocks the effect of water [Column (6)] is greater than that of compression.

The effect of compressing the wet rock [Column (7)] is small in every case, so the corrections for pressure on such porous wet rocks in the Earth will be small and in some cases negligible at all depths for which gradient-measurements are now available.

The conductivities of a few of these rocks (and of others not shown in Table 1) have been measured by another method [Birch and Clark, Amer. J. Sci., v. 238, p. 529, 1940], dry and uncompressed, but in an atmosphere of helium. They are shown in Column (9), and they agree well with the figures in Column (8). Helium is nearly as good a conductor as water, and it may be assumed that it filled some of the pores which water could not enter. This suggests that the conductivities found in the earlier work may be used for wet rocks at depths which we expect to deal with.

Only the reversible effects of compression are shown in Table 1. The permanent change of conductivity produced by a pressure of 10,000 lb/in^2 was negligible except for two specimens; it was six per cent for the marble and eight per cent for the Owl Canyon sandstone. Further investigation will be necessary before the conductivities of such rocks can be estimated with reasonable accuracy.

In conclusion, this work should enable us to make use of certain carefully selected gradient-measurements to estimate heat-flow with an error of not more than five or ten per cent.

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THE RADIOACTIVITY OF ROCKS

Clark Goodman and Robley D. Evans

Introduction

Our knowledge of the physics of the Earth's interior is seriously limited by the extremely restricted range, both of depth and of time, for which direct evidence is available. In addition, the Earth's surface is far from homogeneous and reliable mean values of its physical properties can be obtained only by extensive sampling and measurement. The internal heat of the Earth is one of the features that has received considerable study and about which there has been an even greater amount of speculation. This heat has been credited with supplying the bulk of the energy required in volcanism, petrogenesis, diastrophism, convection-currents, and continental drift.

The main reason for crediting the Earth's internal heat with such all-inclusive effects is that, until recently, it appeared that the rate of generation of heat by the radioactive elements in the Earth was so great that a stable crust could hardly exist. Several rather artificial attempts were made to explain away this anomaly. One of the more feasible of these explanations postulated a rapid decrease in radioactive content with depth; an effect supported to some extent by experimental evidence but not to a sufficient degree to be entirely convincing.

During the three decades following Lord Rayleigh's discovery [see 1 of "References" at end of paper] of the wide-spread distribution of the radioactive elements in rocks, numerous investigators have studied the content of these elements in all types of terrestrial materials. Recent researches indicate that most of these earlier measurements are of qualitative value only. A significant downward revision in the estimated average radioactive content appears necessary. Geophysical considerations based on the earlier values may need to be re-evaluated. In the fol-

Table 1--Comparison of average radioactivities

(Present estimates from Table 10 of reference 3; Jeffreys' estimates as compiled by him [1936, p. 150]; the number given in parentheses below tabular value indicates number of rock-specimens on which average value is based)

Rock-type	Average radium in 10^{-12} g/g rock		Average thorium in 10^{-6} g/g rock		Average (Th/U)-ratio	
	Present estimate	Jeffreys' estimate	Present estimate	Jeffreys' estimate	Present estimate	Jeffreys' estimate
Acidic igneous	1.37 ± 0.17 (43)	2.38 ± 0.16 (122)	13.0 ± 2. (26)	17.6 ± 2.2 (60)	5.0 (26)	2.6 (60)
Intermediate igneous	0.51 ± 0.05 (7)	1.85 ± 0.25 (36)	4.4 ± 1.2 (6)	18.9 ± 8.5 (4)	2.6 (6)	3.6 (4)
Basic igneous	0.38 ± 0.03 (54)	1.03 ± 0.05 (122)	3.9 ± 0.6 (34)	7.8 ± 0.6 (77)	4.0 (34)	2.7 (77)

lowing discussion we will summarize the evidence which leads to this radical change in viewpoint.

Average radioactivities

Since Jeffreys [2] has made a fairly complete summary of the radioactivity-measurements on rocks prior to 1936, a comparison of the newer experimental values with these averages, as given in Table 1, affords a direct indication of the magnitude of this downward revision.

The present estimates for acidic, intermediate, and basic rocks are based on measurements of the number of rock-bodies indicated in parentheses. These data are largely dependent on measurements made by the authors, but include some results by Raitt, Keevil, and Clarke corroborated by direct intercheck measurements [3]. Too few specimens of intermediate rocks have been measured to give significant results. While the number of acidic and basic rocks represented by the present average is only one-half to one-third those included under Jeffreys' averages, still the number is sufficient to be statistically significant. Decreases of 40 per cent in the estimated average radium-content of acidics and of 60 per cent for basics are indicated. Decreases of 25 and 50 per cent in the estimated average thorium-contents of acidics and basics respectively are also indicated. It is of interest to note that the ratio of thorium to uranium is substantially higher than Jeffreys' average. When this ratio is about 4.0, the heating effect due to uranium and its decay-products is equal to that from thorium and its decay-products. Thus these two elements appear to be of about the same geophysical importance. Moreover, the present average (Th/U)-ratios are in better agreement with the value to be expected from isotopic abundance measurements [4] on common lead, provided this lead is derived from ordinary igneous-rock magma.

Reliability of measurements

The question naturally arises as to the validity of these two sets of data. Why should the restricted measurements of the last five years be considered of greater reliability than the more extensive measurements of the preceding 30 years? A detailed answer to this question has been given in a series of papers [5], and there is only space for a brief summary on this occasion.

The techniques of radioactivity-measurements have benefited by the general improvements in sensitive electrical detection-methods during the first third of this Century. Partly as a result of these improvements and partly because of the gradual realization of the precautions necessary, radioactivity-measurements on terrestrial materials have shown a steady decrease in magnitude during this time. This decrease is particularly evident in the case of sea-water studies [6]. Only within the last few years have independent investigators been able to reach anything approaching agreement on the radioactive-content of the hydrosphere, although the best of the earlier workers made numerous determinations. If errors occurred in these measurements, they are certainly to be expected in the more difficult determinations on rocks. When we first began to realize that these uncertainties existed, a systematic program of standardization, calibration, and interchecking was begun. This has now been extended to include all of the known active laboratories in the world. These researches have shown that our primary radium-standard, obtained in 1932 from Dean S. C. Lind, is in agreement with the Physikalisch Technische Reichsanstalt and the recently developed National Bureau of Standards dilute radium-standards within the experimental uncertainty of comparison, that is, a few per cent. All radium-measurements on terrestrial materials are based on a comparison with such standards. Measurements of the standards used by other investigators have shown that systematic errors may arise from faulty standards. To prevent such difficulties in the future, the National Bureau of Standards in cooperation with the National Research Council's Committee on Standards of Radioactivity has recently made available certified radium-standards containing 10^{-9} and 10^{-11} gram of radium and certified rinse solutions to facilitate the use of these standards. Thorium-standards are also under preparation.

Because rocks of a given type vary widely in their radioactive content, we could not be sure that the disagreement between Jeffreys' averages and our present values is real solely from a comparison of the results. Accordingly, a number of intercheck measurements have been made on samples previously measured by the investigators upon whose work Jeffreys' averages depend. In some instances portions of the identical specimen previously analyzed have been remeasured. The differences observed are of the proper direction and magnitude to substantiate the reality of the error in the earlier values. Finally, a recent, very comprehensive comparison of radium-measurements has been made between the Geophysical Laboratory, the National Bureau of Standards, and the Massachusetts Institute of Technology laboratories on 12 standard rock-samples prepared for this purpose. The results are in agreement within the small experimental uncertainties of the measurements. These standard rock-samples are now available for similar comparisons by any other investigators who may desire them.

Heat-generation in rocks

Assuming that the present averages are reliable, what effect does this have on the previous estimates of the rate of generation of heat by radioactivity? Again a direct comparison can be made, because Holmes [7] has made estimates based on essentially the same radioactivity-measurements cited by Jeffreys. In addition the contribution from potassium has been included. Holmes' values are listed together with those based on our present average radioactivities in Table 2. The significant comparisons are for the acidic and basic igneous rocks where it is seen that the present estimates of heat-production in 10^{-6} calory per gram per year are somewhat less than one-third those obtained by Holmes. This decrease is largely due to the lower values of the average radioactivities, but in addition more precise studies of the radioactive properties of potassium subsequent to Holmes' compilation have shown that this element is of much less geothermal significance than previously supposed.

The immediate importance of this revision is that there is no longer an embarrassingly large source of heat in the crustal rocks to plague theoretical geophysicists. As Professor Slichter has shown [8], a factor of one-third in the radioactive-content of crustal rocks allows the existence of a stable crust of a thickness indicated by seismic studies and leaves sufficient additional radioactive material for the mantle and core not to be entirely devoid of these elements. In this way the previously postulated exponential decrease of radioactivity with depth is no longer necessary.

Table 2--Estimates of radioactive heat-generation in rocks

Item	Heat-production in 10^{-6} calory per gram rock per year			
	Acidic igneous	Intermediate igneous	Basic igneous	Sedimentary
Holmes' values[a]				
U............	7.1	6.1	2.5	....
Th...........	4.6	4.1	1.5	....
K............	4.2	3.1	1.7	....
Total.....	15.9	13.3	5.7	....
Present values				
U............	2.2 ±0.2	1.0 ±0.15	0.7 ±0.08	0.9 ±0.09
Th...........	2.6 ±0.4	0.9 ±0.2	0.8 ±0.01	0.7 ±0.1
K............	0.14±0.02	0.10±0.02	0.07±0.01	0.10±0.02
Total.....	5.0 ±0.6	2.0 ±0.4	1.6 ±0.1	1.7 ±0.2

[a] Holmes' classification of igneous rocks into the three broad types differs somewhat from that used in the present discussion; Holmes' values have been rearranged according to the present grouping of rocks as indicated in Tables 1 to 8 of reference 3.

While further measurements on many more terrestrial samples, particularly on ultrabasic rocks, are needed to allow the establishment of more representative average values and to give a firm foundation to these preliminary conclusions, it is comforting to feel that reliable measurements are now possible on a routine basis.

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COOLING OF THE EARTH

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(Abstract)

In Part I observational data and hypotheses pertinent to the colling problem of the Earth are reviewed. The possible importance of heat-transport by slow thermal convection-currents is indicated. In Part II the theory of the cooling of a solid radioactive Earth is presented by a simple method which identifies this problem with an equivalent one in the cooling of a non-radioactive Earth. The facts as to slowness of cooling for temperature-perturbations of long wave-length are reviewed. The importance of the large heat-capacity of the Earth is emphasized by means of simple examples. If the Earth is cooling the rate must be very small, but, if heating occurs, higher rates are possible. Thermal considerations indicate that solidification of the mantle probably occurred from the bottom up. Because the steady-state temperatures in a radioactive Earth are significant in determining whether the Earth is heating or cooling at depth, such temperature-distributions have been computed for a dozen or more types of radioactive earths. It is probable that thermal equilibrium in the Earth as a whole is far from achieved. The Earth may be heating everywhere--cooling everywhere--or heating at some depths and cooling at others. The transient temperatures are expressed, and the transient heat-flows computed for a number of types of suitable radioactive earths which are amenable to convenient computation. The case of heat-flow in layered earths is especially examined. The observed surface heat-flows fix definite upper limits to the total heat-generation which may exist within about 100 or 200 km of the surface. It is important to improve the reliability and scope of present information concerning (1) surface heat-flows, (2) the structure and composition of the crust, and (3) the association of heat-generation with crustal layers. Until better knowledge of all three of these factors in the same region is available, estimates of the amount of radioactivity existing in and below the crust will involve large uncertainties. Even granting excellent thermal information about the crust, it is possible to deduce by thermal theory only very limited information about regions below a depth of 200 or 300 km. Little correlation exists between the radioactivity at depth and observed surface heat-flux. Heat-generation of the order 10^{-14} cal/cc/sec, or 10 per cent of that observed in plateau basalts, may exist at all depths, to the center, without producing effects contrary to the facts of observation. No need is found for a drastic rate of decrease of radioactive substance with depth. The oft-expressed idea that the indicated amounts of radioactivity in the Earth are embarrassingly large and greatly exceed the amounts to be expected from observed surface heat-flows is fallacious.

[Note: The complete paper is published in Bull. Geol. Soc. Amer., v. 52, pp. 561-600, 1941.]

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CYCLIC CONVECTION-CURRENTS

Harvey Brooks

This paper presents the results of some speculations concerning the existence and geologic effects of convection-currents in the Earth's substratum, the so-called silicate shell extending, according to the best evidence, some 3,000 km below the bottom of the Earth's outer crust. The possibility of the existence of such currents has been amply demonstrated by the calculations of Pekeris [see 1 of "References" at end of paper] and others. It is quite true that the mere existence of an unstable temperature-gradient will not of itself cause convection provided the substratum has a fundamental strength, but, as Pekeris has shown, a horizontal temperature-variation of several tens of degrees would set up sufficient stress to overcome the fundamental strength. In the present work we have made a somewhat more careful estimate of the stresses existing in an elastic body due to various types of thermal perturbations, and the results confirm Pekeris almost exactly, namely, the maximum stress is about 5 kg/cm^2 per degree of horizontal temperature-difference, so that even with an assumed strength of 100 kg/cm^2, convection would start with a temperature-contrast of about 20°, such as could easily be set by irregularities in the cooling of the Earth.

The question of convection naturally divides into two parts. The first part is primarily concerned with the role of convection-currents in orogenic processes. Certainly it can be shown that the tangential forces exerted at the base of the crust would be sufficient to account for the observed folding and, as has been pointed out by Griggs [2] and Pekeris, the convection-theory has the big advantage that it gives a natural explanation of the localization of the compressive stresses in narrow regions of the crust, these regions being defined by the convergence of the horizontal currents. This aspect of the matter, however, is more amenable to investigation by means of scale-models, and by actual geological observation, than by mathematical methods, and so we leave the discussion of this problem to the geologist.

The second part of the problem is purely thermal, and concerns itself with the part played by convection in the thermal history of the Earth. Here mathematical methods become useful, because we cannot investigate the substratum directly, nor can we reproduce the thermal effects with scale-models. Most of the previous mathematical treatments of convection in the Earth have largely ignored the matter of thermal transport, and so have been based either implicitly or explicitly on the hypothesis of a steady state. Pekeris rightly points out that if a temperature-variation is maintained which does not coincide in direction with gravity, then convection will take place regardless of the vertical stability. However, this convection will be damped out very rapidly unless the vertical lapse-rate considerably exceeds the adiabatic, because convective transport will destroy any horizontal temperature-perturbation much more rapidly than it can be reestablished either by conductive processes or by radioactive heat-generation. Indeed, the realizable steady-state velocities will be of the order of several thousand times smaller than the velocities of a few centimeters per year tabulated by Pekeris, so that in the long run the transport of heat by convection cannot greatly exceed the transport by conduction. However, if there is an unstable temperature-gradient, any vertical motion will tend to increase the horizontal temperature-contrast and so accelerate the motion, so that initially the convection may accelerate very rapidly. Of course, the superadiabatic gradient will eventually be destroyed

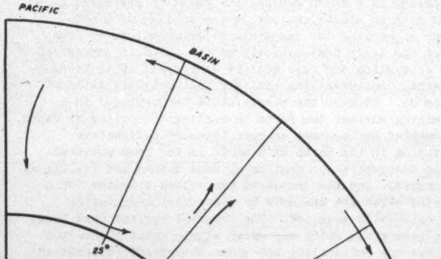

Fig. 1--Successive states in the development of the hypothetical convection-cycle of Griggs

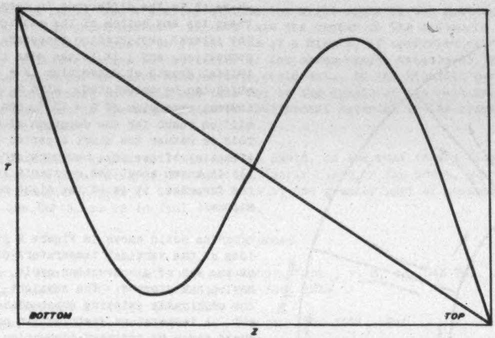

Fig. 2--Section of vertical temperature-distribution at the end of a convection-cycle

by this process as sufficient hot material is brought up from the bottom to blanket the instability, but in the meantime convection-velocities of considerable geologic importance will have been attained, and only if there is large preexisting unstable gradient can such velocities exist. Such an unstable gradient would exist in the Earth's substratum as a consequence of current theories of the solidification of the mantle, which is believed to have taken place from the bottom up, so that the temperature-distribution would be governed by the change of melting point with pressure, which considerably exceeds the adiabatic gradient for the materials composing the substratum.

The above considerations indicate that if convection is to play any important part in geology it must be intermittent in character, simply because there is insufficient energy-supply to keep it going at a rate sufficient to be geologically observable. This possibility of cyclic convection was first brought forward by Griggs [2], who pointed out that the existence of a fundamental strength would prevent the initiation of convection-currents until sufficient horizontal temperature-contrast had built up, and that then convection would accelerate rapidly in the presence of an unstable gradient, owing partly to the decrease of viscosity with increasing stress which is characteristic of the so-called "pseudo-viscous" flow of many solid materials. At any rate the fundamental strength would allow the presence of a high unstable gradient, without convection starting immediately, which seems to be an essential feature of the cyclic process.

We have subjected to rather careful mathematical analysis the problem of the development of convection-currents in the course of time from an initial form of temperature-perturbation and superadiabatic gradient. We shall not go into the mathematical detail here except to remark that the present method takes into account in an approximate fashion the non-linear terms in the equation for heat-transport, so that the analysis applies to the decelerating phase of the cycle as well as to the accelerating. It can be shown that the cycle is approximately symmetrical in time. During the later stages of the motion, however, the convection tends to dissipate itself into smaller and smaller cells, so that the decelerating phase will be slightly prolonged. The maximum convection-velocities occur when the horizontal difference in temperature has been built up to a point where it is nearly equal to the original vertical difference. With a kinematic viscosity of 3×10^{21} cgs units [3], and an original vertical difference of 500° in excess of the adiabatic, the initial velocity would be of the order of five cm/year; the maximum would be 70 cm/year or larger if one took account of the change of viscosity with stress; while during the fastest part of the motion shearing stresses of over 1,000 kg/cm^2 on the under side of the crust might be attained.

The mathematics gives a simple formula for the total period of the cycle, if we know the fundamental strength, the viscosity, the unstable gradient, and the coefficient of thermal expansion. This takes the form

$$t = (2/\gamma)\,\ell n\ 0.9\,(\Delta T/V_0)$$

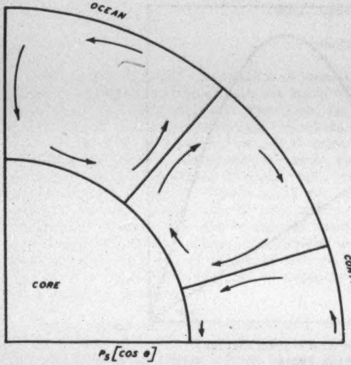

Fig. 3--Shows optimum system of connection cells corresponding to mode P_5 [cos θ]

where ΔT is the difference in temperature between top and bottom of the substratum, V_0 is the lateral perturbation necessary to initiate convection, and 1.1γ is the mean life for the initial growth of convection ($V = V_0 e^{\gamma t}$), which can be calculated. With $V_0 = 20°$ and a thermal expansion of 2×10^{-5}, one obtains 12 million years for the duration of a cycle. This is rather too short a period from the viewpoint of geology, but considering how little is known about the constants involved in the formulas, it is of the right order of magnitude.

The solid curve in Figure 2 gives a rough idea of the vertical temperature-distribution at the end of a convection-cycle, after the motion has stopped. The straight line shows the originally existing superadiabatic gradient. A temperature-distribution of this type would decay by ordinary conduction exponentially with a mean life of 6.8 billion years, which would imply that the unstable gradient had not had time to reestablish itself since the solidification of the substratum. On the other hand, it is probable that the flow is of the pseudo-viscous type exhibited by stressed solids under laboratory conditions, in which the viscosity decreases rapidly with the applied stress. It is not possible to give a rigorous solution of the convection-equations in the case of pseudo-viscous [4] flow, but we have obtained an approximate result for one case, which gives a good idea at least of the direction in which the results should be modified. One finds that the motion is relatively more concentrated towards the outer edge of the cell than in ordinary flow and that, therefore, the hot and cold strata shown in the diagram will be relatively much thinner, and will hence lose their temperature-difference more rapidly than we have calculated.

The heat actually conveyed from the interior by a convection-cycle is much less than one might at first expect. Even with the assumption most favorable for heat-loss, namely, that of an infinitely conducting crust, the heat-loss due to convection during the life-history of the Earth would be less than four times the heat-loss due to conduction during the same period. The reason for this is that, owing to the rigidity of the crust and the very high viscosity of the substratum, heat cannot be transported by convection all the way to the bottom of the crust, but must be carried away by conduction, which is an extremely slow process. Thus the large thermal inertia of the Earth, emphasized by Slichter, limits even the convective-transport of heat.

There is another question which geologists may well ask, and that is, what does the convection-theory have to say concerning the distribution of mountain building on the surface of the Earth? We have also considered this question in some detail, and would like to present a highly tentative and speculative picture based on the results of the mathematical analysis. One of the difficulties of the theory presented by Pekeris, it appears, is that it requires convection-currents which are rising under the continents and descending under the oceans, whereas we are fairly sure that the tectogene is produced at the convergence of horizontal currents, that is, over the descending currents where the compressional stress on the crust reaches a maximum. Now, every convection-problem can be analyzed into fundamental modes of motion, each of which, in the presence of an initial superadiabatic gradient, grows exponentially with the time, but each with a different exponential factor depending on the size of the corresponding convection-cell. In every case there is one particular cell-size that grows more rapidly than any other. For the problem at hand the optimum system of cells is illustrated in Figure 3. If cooling begins, for example, over the center of the Pacific Basin, where the crust is both thin and low in radioactive content, then descending currents will be generated there, and a cell-system similar to that shown in Figure 3 will rapidly be formed, the successive cells being arranged in the form of annular rings or zones surrounding the center. This is different from the polygonal pattern usually observed in plane convection, not only because we are here dealing with the spherical case, but primarily because there exists a region of maximum cooling which provides, a center from which the convection-system originates. It is seen from Figure 3 that the first tectogene will occur in the form of a circle of radius 73° surrounding the center of the Pacific. It is tempting to believe that this may be the origin of the great system of mountains which encircles the Pacific Basin, and a similar explanation might apply to the systems associated with the Atlantic and Indian ocean-basins. In each case the center of the system is an ocean-basin, and the associated mountain system is in the form of a circle, of approximately 73° radius about the center. No tectogene occurs in the center of the ocean-basin, because of the absence of light continental material on which the currents could act. In the Atlantic Basin there is a small amount of continental material, and this may be the origin of the well-known mid-Atlantic swell, which is then due to the segregation of continental material by the converging currents under the Atlantic Basin.

If the above picture is correct, the Pacific Basin, as the most recent site of a convection-system, should have a great deal of hot material fairly close to the crust, as shown by Figure 2. We might thus reasonably expect it to be the site of the greater part of volcanic activity on the surface of the Earth, as is in fact the case.

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CONCLUDING REMARKS RELATIVE TO THE THERMAL HISTORY OF THE EARTH

L. H. Adams

The problem of the cooling of the Earth is one of extraordinary complexity and at times seems impossible of solution. In order to make any progress in this important field, it is necessary to make some sort of a start. It would undoubtedly be useful to begin with any reasonable set of initial conditions and to find what this leads to, with a view to modifying and improving our preliminary concepts. As a step towards unraveling the tangled threads, I would propose to start with three hypotheses: (I) The interior is vastly different in composition from the materials near the surface; (II) the Earth was originally molten and well stirred by convection; and (III) the mantle solidified from the bottom upward.

That the first hypothesis is a reasonable one is strongly indicated by seismological evidence, which shows great changes in properties of rocks within a few tens of kilometers of the Earth's surface. Positive evidence is also supplied by the known facts of radioactivity. If the interior were not markedly different from the surface in content of radioactive elements, then the interior would be increasing in temperature at an appreciable rate. The importance of such a condition lies, not so much in the conclusion that the Earth as a whole would be heating rather than cooling, as in the fact that by extrapolation backwards a temperature of absolute zero would be reached in a geologically rather short time. The possibility and probability that the Earth (except for the metallic core) solidified from the bottom upward was pointed out by the author in 1924. An even more cogent reason for believing that the interior is quite low in radioactive elements (as emphasized by Jeffreys) is that otherwise the thermal gradient near the surface would be too high. This mechanism now appears to be finding increasing favor.

In this connection, it may be worth while to call attention to a few simple theoretical and experimental relations the applicability of which is not generally appreciated. In the first place, heavy materials do not segregate (to any significant extent) towards the bottom of a liquid layer except by a separation of phase, for example, by the presence of immiscible liquids, by crystallization, or by the formation of gas-bubbles. In the second place, crystallization in silicate mixtures can produce a remarkably sharp separation of the various components. Striking examples may be found in the recent silicate studies at the Geophysical Laboratory of the Carnegie Institution of Washington. Systems containing an early-crystallizing mineral, such as diopside or olivine, will still produce pure crystalline diopside or olivine when the liquid contains a little more than two per cent of one of these components. Another experimental fact of far-reaching importance is that an olivine rock can have a vanishingly small radium-content. Recent measurements at the Massachusetts Institute of Technology and at the Geophysical Laboratory on a Balsam Gap, North Carolina, dunite consisting almost entirely of olivine showed a radium-content scarcely higher than the overall uncertainty of such measurements. Indeed, so far as radioactive elements are concerned, this is one of the purest known materials. No longer is it necessary to trouble ourselves with what has been an outstanding puzzle, namely, how to get rid of the heat produced within the Earth by the radioactive elements that formerly appeared to exist in notable quantities in all types of rocks. It is, of course, quite likely that this dunite is not similar in all respects to what might be alleged to constitute the bulk of the Earth's interior. It does show, however, that it is possible to form large masses of olivine essentially free from uranium and thorium.

It appears that it would be profitable to explore further the implications of the above-mentioned set of hypotheses. In brief, the early history of the Earth would be as follows. Shortly after liquefaction of the originally gaseous material, the iron core settled towards the center because the metallic phase is immiscible with the silicate one. The material outside the core at that time might well have consisted of a liquid having the composition of magnesium, iron, orthosilicate, in addition to, say, 0.4 per cent Al_2O_3, 0.2 per cent alkalis, 0.1 per cent CaO, a small quantity of water, and traces of other elements, including minute quantities of uranium and thorium. Crystallization of such a magma, as we now know, must inevitably have produced an olivine rock until only the crustal layer remained. There is good reason to believe that differentiation by crystal settling would produce a very pure olivine, and if the crystallization was by the slow thickening of a layer at the bottom, a still higher degree of purity would be obtained. If is quite reasonable that a sharp separation of uranium and thorium would take place and that the body of the Earth would thus be extraordinarily free from the radioactive elements.

The point upon which emphasis is now being placed is the desirability of basing thermal studies of the Earth's interior upon various sets of reasonable hypotheses rather than to attempt a single, rigorous, and general solution; that the outstanding property of the Earth is the difference in composition of the Earth's interior and its superficial layers; and that the only mechanism for accomplishing this that would be acceptable to an experimental petrologist is by some sort of crystallization-differentiation.

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THE PROBLEM OF IDENTIFYING THE CRUSTAL LAYERS

Francis Birch

Our most detailed information regarding the inaccessible portions of the uppermost 35 or 40 km of the Earth comes from the interpretation of seismic records of "near" earthquakes and of quarry-blasts. These records are used to obtain velocities and structures; as a first approximation, these structures are taken to be horizontally uniform layers with the velocities, in each layer, independent of the depth. Average velocities and layer-thicknesses are computed with these assumptions. Two of the best sets of results of this kind are shown in Figure 1, for New England by Leet, and for Southern California by Gutenberg. The problem which I wish to consider is the use of such material in arriving at a more concrete description of the constitution of the region down to 40 km.

In the determination of velocities and thicknesses of layers, the seismologist may ignore such factors as the composition or temperature of these layers, but these factors are of fundamental importance for many geological problems. We may suppose, however, that when we possess adequate information concerning the velocity of wave-propagation in all possible materials, a careful juxtaposition of velocities in known materials with velocities in the various layers will enable us to decide, first, which materials definitely do not fit, and finally, guided by geological probabilities, which materials are at least not inconsistent. We have to be prepared to find some ambiguity, or at least, insensitivity in this method. It is assumed in such a procedure that the minerals at present existing in these layers are among those which are familiar to us at the surface, and thus available for experimental work. At best, we can determine only possible materials; there may be more than one set of possible materials, so far as velocities alone are concerned. Finally, we must take into account the probable physical conditions at the depths of the layers in question. These conditions must be simplified for our purposes; we assume that it is sufficient to consider only two physical variables, temperature and mean stress, each of which is a function of the depth. Estimates of these quantities are shown at the bottom of Figure 1; they are not very different from many other such estimates. The important point to remember is that when we speak of a layer at a depth of from 15 to 20 km, we are speaking of material at a mean stress of from 4,000 to 5,000 kg/cm^2, and a mean temperature of perhaps 300° to 400° C; and so on for the other depths.

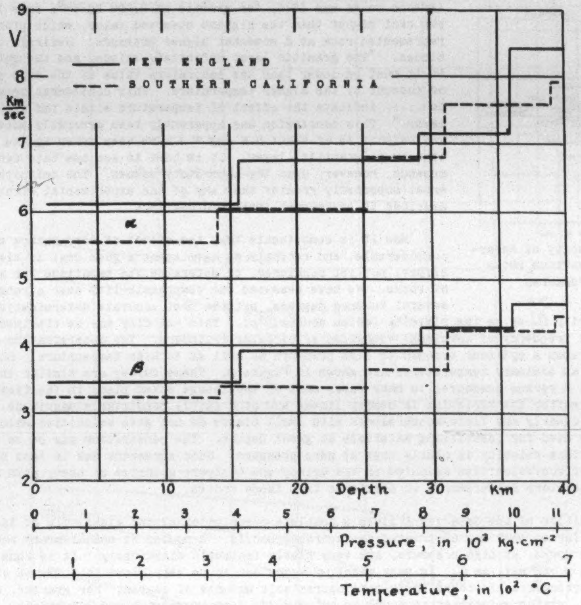

Fig. 1--Velocities as function of depth in New England, after Leet, and in Southern California, after Gutenberg; estimated pressures and temperatures as function of depth

The first measurements which were of any use in dealing with this problem were the determinations of the compressibility of rocks and minerals to hydrostatic pressures of 12,000 kg/cm^2, at ordinary temperature, by Adams and Williamson, with later additional determinations by Adams and Gibson. These measurements showed, for the first time, that at high pressures the elasticity of known surface-rocks was sufficiently high to account for most, if not all, of the velocities assigned to the crustal layers.

Compressibility-measurements can be used for comparison with seismic velocities in two ways. If 1/K denotes the compressibility and ρ the density, then the velocity α of the compressional wave is given by $\alpha^2 = (3K/\rho)\ [(1 - \sigma)/(1 + \sigma)]$ and the velocity β of the shear wave by $\beta^2 = (3K/2\rho)\ [(1 - 2\sigma)/(1 + \sigma)]$ where σ is Poisson's ratio. Adams and Williamson calculated velocities by assuming a value 0.27 for σ for all rocks and minerals. This method has the disadvantage of introducing this somewhat arbitrary assumption; moreover, for a given K, the velocities, especially β, are rather sensitive to variations of σ. A second method of comparison was adopted by Jeffreys, who noticed that $(K/\rho) = [\alpha^2 - (4/3)\beta^2]$. Thus (K/ρ) can be computed for each layer and compared with the measured values of (K/ρ) for various rocks. No new assumptions are required here, but the method evidently sacrifices some of the precision of the velocity-determinations; furthermore, there may be a number of different pairs of velocities which give the same difference of their squares.

It may be well to recall here the actual figures used by Jeffreys and his conclusions, in order to appreciate the spirit in which this method was used. I shall consider only the upper layer. Here Jeffreys used the velocities $\alpha = 5.4$ to 5.6 km/sec, $\beta = 3.3$ km/sec, whence $(K/\rho) = 14.7$ to 16.9 (km/sec)^2. Now from the compressibility-data, the lowest value of (K/ρ) for

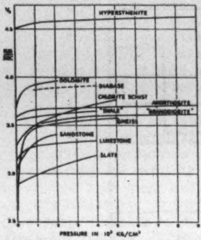

Fig. 2--Velocity of shear-waves in various rocks at high pressures

igneous rocks was 18.3, for granite at 2,000 kg/cm^2; this is eight per cent higher than the highest observed value, which presumably represented rock at a somewhat higher pressure. Jeffreys concludes: "The granitic layer definitely exists, and the bulk modulus in it must be lower than the laboratory value at the same pressure, on account of the higher temperature. This consideration seems to ..... indicate the effect of temperature within the granitic layer." This conclusion has apparently been generally accepted, and velocities of about 5.6 and 3.3 have been taken as the velocities in a "granitic" layer. It is hard to see how this conclusion depends, however, upon the laboratory values. The definite difference, supposedly greater than any of the experimental errors, is ascribed to an unknown temperature-effect.

Now it is conceivable that the effect of temperature may be considerable, and recently we have spent a good deal of time in an effort, not yet concluded, to determine its magnitude for a variety of rocks. We have measured the compressibility over a range of several hundred degrees, but the most accurate determinations apply to the velocity β, or to the rigidity (which equals $\beta^2\rho$). This velocity may be obtained from the resonant frequency of torsional vibration of circular cylinders. The determination may be carried out upon a cylinder exposed to high pressure as well as to high temperature. Some of the results at ordinary temperatures are shown in Figure 2. These curves are similar in shape to curves of K versus pressure; in many cases most of the change takes place in the first 1,000 kg/cm^2; thereafter the variation is nearly linear and of a fairly predictable magnitude. These curves show clearly why field-measurements with small blasts do not give velocities which may be uncritically used for identifying materials at great depths. The penetration may be so small that the surface-velocity is nearly that at zero pressure. Good agreement has in fact been found for surface-velocities measured in the Quincy and Rockport granites by Leet, with the low-pressure laboratory measurements on specimens from these bodies.

The addition of the data for β gives a complete description of the elasticity of the materials, in so far as they may be treated as isotropic bodies. A number of measurements have shown that igneous rocks, at high pressure, are very nearly isotropic elastically. It is thus possible to calculate α, as well as σ. In many cases, σ turns out to be very close to 0.27; in others it is lower, particularly in rocks containing appreciable amounts of quartz. For granite, we find σ about 0.24, giving velocities at 4,000 kg/cm^2 and 30° C of around 6.1 and 3.5 km/sec. Again, these are about ten per cent higher than the values attributed to "granite" by Jeffreys and others.

Now what is the effect of temperature? This cannot be determined over a wide range for rocks by measurements at ordinary pressure; it is necessary that the rocks be under considerable pressure if they are not to disintegrate as a result of the unequal expansion of the various minerals. As a beginning, we determined the effect of temperature on β to 150° C, and 4,000 kg/cm^2. For granites, this velocity decreased at the rate of four per cent per 1,000° C rise of temperature; such a coefficient would evidently require temperatures greatly in excess of those that we are willing to admit in the uppermost 15 km in order to reconcile the velocities in laboratory granite with those in Jeffreys' upper layer. But it was clear that the experimental temperature-range should, if possible, be extended to the temperatures actually expected in the "granitic" layer, perhaps 500° C at most, since any departure from the coefficient observed with lower temperatures would be toward lower velocities. Such measurements have now been made and Figure 3 shows some of our present results. The numerals besides the names of the rocks indicate the pressure, in thousands of kg/cm^2. The granite shown here is from Barre, Vermont. Others will doubtless show somewhat different results. The total decrease of β for this granite, to 500° C, is about two per cent, or just about what we obtained by using the former coefficient. Above 500°, however, there is a definite departure from linearity partly as a result of the approach to the quartz inversion-point, at this pressure about 670° C.

As a consequence of this small temperature-effect, it seems very unlikely that the velocities in any rock very similar mineralogically to granite can be much below 5.9 and 3.4 km/sec in layers extending to 15 km or more except within a few km from the surface. Thus, on comparing the velocity-depth curves of Figure 1 with these values, I should say that the top layer in New England and the second layer in Southern California are probably very similar and not far from granite in composition. It seems reasonable to believe that the basement-complex, predominantly granitic, comes very close to the surface in New England. How to account for about 14 km of

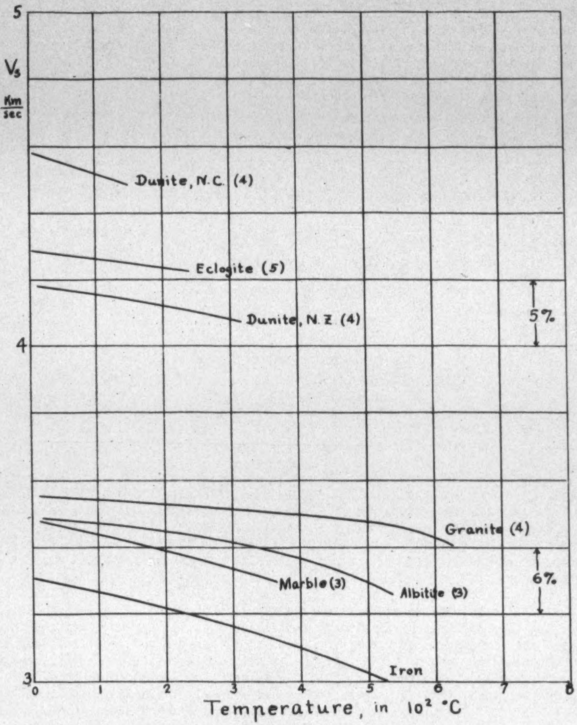

Fig. 3--Effect of temperature upon the velocity of shear-waves in various rocks at high pressures

something else above the basement in Southern California presents a problem. A possible way out might be to admit a moderate proportion, on the upper part of the California crust, of sedimentary material of lower velocity. If about 16 per cent of the path were through material having $\alpha = 4$ km/sec, while the rest had $\alpha = 6$ km/sec, the mean velocity would be the observed 5.6 km/sec. A velocity of 4 km/sec (13,000 ft/sec) is by no means a low velocity for Tertiary sediments. Such a conception is probably open to objections on various grounds. But it seems clear that there is no basis in laboratory measurements for describing a layer with velocities of 5.6 and 3.3 as "granitic"; it may of course be granite plus an indeterminate amount of material of lower velocity, of non-igneous origin.

We have not time to discuss all the other layers, but perhaps a word may be said about the bottom one. This has been generally regarded as probably mainly olivine or dunite, since this is the rock which gives the highest known velocities, and indeed velocities which, at ordinary temperature, seem to be about as high as the seismic velocities just below the upper layers. The effect of temperature on this material, so far as we know it at present, is shown in Figure 3. The velocity β is highest in the dunite from Webster, North Carolina, but its rate of decrease is also the highest. The dunite from New Zealand shows a somewhat lower velocity, and a smaller rate of decrease. We hope to carry these measurements on dunite to 600° C. However, unless there is a change of phase, it seems that the velocities in dunite will be considerably lower at the appropriate temperatures than the velocities ascribed to a depth of 40 km in Southern California, and very much lower than the velocities at 36 km in New England. Eclogite may fit somewhat better, but it looks as though its velocity also will be too low. About the only silicate which appears to be possible for this deep layer is some variety of garnet, for which we have no measurements at present on the effect of temperature.

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WAVE-ANALYSIS AS A CLUE TO THE MECHANICS OF EARTHQUAKES

L. Don Leet

No abstract or manuscript was submitted for this paper.

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TECTONIC PROCESSES NOW IN ACTION

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Institute of Technology, Contribution No. 313)

Tectonic processes may act either gradually as in connection with plastic flow, or as sudden movements connected with earthquakes. The first sort of movements requires that in a layer the stresses are larger than the strength of the material in opposing plastic or pseudo-plastic flow; the second that somewhere they surpass the breaking strength. In three papers [see 1, 2, 3 of "References" at end of paper], one of them jointly with Dr. Richter, the author recently has investigated such processes. In the present paper, it is intended to give a summary and to draw certain conclusions.

From the fact that mountains apparently have not changed their height appreciably in historic times and also from laboratory experiments it follows that in the uppermost layers (at least 30 km thick) the strength is of the order of 10^9 to 10^{10} dynes per cm^2. Isostasy and postglacial uplift, on the other hand, indicate that below this depth the strength decreases rapidly. A disturbance of the equilibrium corresponding to the weight of an extended layer of rock with a thickness measured in several tens of meters produces subcrustal flow reaching probably down to the core of the Earth [1]. Seismic observations [4], since confirmed by unpublished results, lead to the conclusion that at a depth of about 70 km there is a small but definite decrease in the wave-velocity, possibly indicating the transition from the crystalline to the vitreous state of the material there. This would explain a decrease in strength at this depth.

The order of magnitude of the strength below a depth of 70 km is not known. Its value is of importance for an estimate of the minimum stresses required to maintain plastic flow. The relatively small stresses required to produce changes in marginal areas of post-glacial uplift suggest the possibility that forces even as small as the "Polfluchtkraft" may produce noticeable plastic flow over long periods. On the other hand, it seems safe to conclude that the relatively large gravity-anomalies in tectonically active regions are connected with subcrustal movements extending to the core of the Earth. The velocity of these subcrustal currents depends mainly upon the viscosity of the material and the stresses. In areas of post-glacial uplift, it takes thousands of years to reduce deviations from the equilibrium to one-half, which denotes an average viscosity of the order of 10^{22} poises.

Gravity-anomalies at the surface of the Earth indicate stresses acting at an unknown depth at present or very recently. In many regions, they at least serve to maintain the deviation from the equilibrium. The seismic activity in such regions shows that the stresses frequently surpass the breaking strength of the material. Deep-focus earthquakes furnish proof that in certain areas down to a depth of 700 km the stresses are accumulating faster than plastic flow can reduce them. On the other hand, all evidence indicates that a larger part of the tectonic activity of the Earth occurs in relatively narrow belts surrounding the Pacific Basin [2]. The sequence of phenomena observed in these belts is quite persistent, although data are incomplete in most of them. Proceeding from the ocean towards the continent, usually the oceanic basin descends into a deeper trench. No seismic activity is found there. Earthquakes with focal depths less than 50 km occur chiefly beneath the steep slope extending upward from this trough to the continent. Moreover, along this slope is a belt of maximum negative gravity-anomalies. On land the gravity-anomalies become positive and are frequently associated with volcanism and shocks at increasing depths, usually not exceeding 150 km. Still farther inland under mountain ranges of about tertiary age, there is sometimes a belt of foci at depths exceeding 150 km, sometimes even approaching 300 km. Farther inland still, shocks may be found at depths ranging from 300 to 700 km but without clear relationship to surface structures in the immediate neighborhood. In some regions the foci of the earthquakes appear to fall on a surface dipping at various angles downward away from the ocean. However, in no region is there conclusive evidence that this whole surface is active. Possibly, it is a surface of maximum stress.

There is no evidence thus far of earthquakes originating at depths appreciably exceeding 700 km. Either the stresses decrease there noticeably, or the viscosity decreases, permitting a more rapid plastic flow, or there is a noticeable increase in the breaking strength. The fact that the very deep shocks frequently exhibit large energy might be a consequence of a larger breaking strength which also could be expected from the theoretical conclusions of Goranson [5].

Most of the remaining major seismic activity occurs in the Tertiary mountain ranges in southern Asia and southeastern Europe, where shocks at depths not exceeding 50 km follow most structural trend lines of Tertiary age, and where there are also foci at greater depths, but not exceeding 300 km. There are, finally, narrow belts of shallow foci beneath the mid-Atlantic ridge and beneath ridges in the Indian Ocean. These belts, however, differ in so many respects (absence of deep foci, small gravity-anomalies, occurrence under ridges, far from trenches) from the belts surrounding the Pacific Basin that a completely different source for the stresses seems highly probable. Gutenberg and Richter [2] have pointed out the frequent close coincidence of the active zones outside the Pacific Basin with the orogens of Kober. However, this agreement does not include the bottom of the Pacific Basin, which, except for shocks near Hawaii, seems to be one of the least active regions of the world. In general, this area is clearly outlined by petrographic evidence (Andesite line), earthquake-epicenters, and changes in the velocities of seismic waves. Only along the south and southeast is there some doubt about the exact boundary, which, in general, seems there to follow the Easter Island Ridge and its continuation towards southwest and west. There is fair evidence of some outlying patches of Pacific structure, as in the Gulf of Mexico, in the Southern Antillean Region, in the Philippine Basin, and in the Arctic Basin.

The results of investigations of compressions and dilatations at the beginning of earthquake records, as well as geological evidence, leave no doubt that the directions of the crustal movements do not scatter at random. In Japan (according to Ch. Tsuboi) and in the Philippine Islands (according to B. Willis) the continental side is moving southward relative to the Pacific Basin. In Southern California and parts of Central California this is true, too, for the movements along the major faults during recent times; and at present the initial impulses in even the smallest shocks occurring along minor faults generally indicate the same type of movement [3]. Shearing stresses are continually straining this region in a way similar to that when a sheet of paper is deformed by moving two opposite sides in opposite directions. Although this horizontal shear has formed, for example, the San Andreas Rift which has a known length of over 1,000 km, it would be premature to conclude that shearing stresses of this type have produced the large mountain systems and are the cause of all the major tectonic processes at present. These shearing stresses may be due to a minor but permanently acting force, for example, to the "Polfluchtkraft".

The stresses which indirectly are the source of the gravity-anomalies and ocean-deeps around the Pacific Basin, seem to be directed more radially in respect to the ocean and are probably connected with much larger energies than the shearing stresses discussed above. Models of the mechanism of the processes and experiments related to them have been described by Kuenen [6] and by Griggs [7]. From the observations, it seems likely that this mechanism is not symmetric to the boundary-surface of the Pacific Basin. From various points of view, Du Toit, Andrews, and others at the Sixth Pacific Science Congress defended the well-known idea that the continental layers surrounding the Pacific Basin are encroaching on the ocean-bottom and are being warped down. A subcrustal movement returning towards the continent at depth would fit into this picture and would not disagree with the other observations. This might even prove a key to the puzzle of the submarine canyons in the Pacific, whereas in the Atlantic the assumption of thinning of the ocean-bottom could have produced a sinking of the shelf-region (according to Du Toit and Maxson).

The problem of the energy required for these processes is completely unsolved. Differences in temperature between the deeper layers beneath the continents and the Pacific, differences in radioactive content, and chemical processes are among the possible sources. It is not unlikely that the mechanism in tectonic processes in other regions is quite different. Only accumulation of more observations of various kinds including earthquakes, volcanoes, submarine topography (especially submarine canyons), gravity-anomalies, magnetic anomalies, petrographic data, and a careful discussion of all will make it possible to discriminate between various hypotheses in a given region and to arrive at a picture which may be called a first approximation for the tectonic processes at present in action. Only after this goal has been reached, may conclusions be drawn as to the processes involved in the history, considering, however, that the present tectonic processes may not be characteristic of the whole history of the Earth.

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AMERICAN GEOPHYSICAL UNION

TWENTY-SECOND ANNUAL MEETING

APRIL 30 – MAY 3, 1941

SECTION OF HYDROLOGY

PAPERS

WASHINGTON, D. C.
MAY 1, 2, 3, 1941

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TWENTY-SECOND ANNUAL MEETING (1941)
MINUTES, GENERAL ASSEMBLIES AND SECTIONS,

BUSINESS SESSION

The Business Session of the General Assembly of the American Geophysical Union was held Friday, May 2, 1941, in the Library of the National Academy - Research Council Building, Washington, D. C. The Session was called to order at 12:00 noon by the President, R. M. Field, there being 64 members present [see Appendix A].

The minutes of the General Assembly of the Twenty-First Annual Meeting on April 26, 1940, were approved as published in the Transactions of 1940.

The General Secretary's report for the year [see Appendix B], presented in abstract, was accepted and ordered printed in full in the Transactions of 1941.

Reports of standing committees

Chairman Rappleye of the Membership Committee reported that the activities of the Committee during the past year consisted largely in receiving applications, passing on them, and correspondence with various members of the Committee. He stated that the Committee was postponing until after the change of officers on July 1, 1941, and the possible change in membership of his Committee, the intensive drive for members which he had been instructed to instigate.

Chairman Avers of the Budget Committee reported that his Committee preferred to wait until a little later in the year to prepare the budget for the year beginning July 1, 1941.

Chairman Lowdermilk of the Committee on Meetings felt that the meetings had spoken for the work of the Committee. He expressed regret that more members were not able to hear the presidential address of Dr. Field on the evening of April 30.

Chairman Fleming of the Editorial and Publication Committee reported that we must expect an increase in the cost of publishing the Transactions because of the higher cost of paper and of skilled labor required, and that it would be helpful if all who contributed to the program would turn in their manuscripts at the earliest possible moment. He also stated that the greater portion of the master-copy for the Regional Meeting at Sacramento had already been completed.

Reports of special committees

Chairman Fleming of the Special Committee to Cooperate and Advise with the Division of Physical Sciences of National Research Council in Publication of Bulletins on Geophysical Methods, etc., reported that Dr. Meinzer had made considerable headway on the volume pertaining to Hydrology, which is the last one of the series "Physics of the Earth" to be published, and that the two previous volumes of this series had enjoyed good sales and distribution.

In the absence of Chairman Ewing of the Special Committee on Geophysical and Geological Study of Oceanic Basins, Dr. Hess reported that most of the Committee's work has to do with National Defense but that some work is continuing in the West Indies, where there will be several men working this summer. He added that certain additional information has been obtained from oil companies on gravity-relations at various places.

Chairman Thom of the Special Committee on Geophysical and Geological Study of Continents reported that the activities of his Committee were mostly informal and cooperative, keeping in touch with members of other organizations and oil companies. He further reported as follows: "A matter of satisfaction is the availability through the Humble Oil Company of a gravimeter which we have been able to reloan to the Geological Society of America for an interesting program of research which they have conducted during the past year and which will go forward during the coming year. Certain other of the Committee's activities have culminated in the present Section of Tectonophysics, which is being most helpful. Much of the work which was previously in our hands will now be in the hands of that Section."

In the absence of Chairman Swick of the Auditing Committee, Dr. Fleming reported that the Committee had made a thorough audit of the books and accounts of the Union and found them to be correct in every way through the year ending December 31, 1940.

Chairman McComb of the Special Committee on Time-Signal Service read the following report of his Committee (M. Ewing, W. A. Marrison, H. E. McComb, Paul Sollenberger, H. T. Stetson, C. H. Swick, and H. O. Wood):

"This Committee has continued its efforts to keep in touch with organizations using United States Naval Observatory time-signals as broadcast by the Naval Communications Service.

"In addition to the splendid schedule of time-signals as broadcast on a wide range of frequencies from a number of Naval radio stations, there is need for the resumption of the 17-kc signal for use in studies of the propagation of radio waves and in investigations of the ionosphere.

"The continuation of the 115-kc signal from NPG, San Francisco, is of immense value in the work of the seismological stations on the Pacific Coast. These signals are broadcast on a four-hour schedule. It is hoped that they can be placed on an hourly basis as soon as conditions permit.

"There has been marked improvement in the promptness with which the time-signal corrections for scientific purposes have been distributed from the Naval Observatory."

Chairman Stetson summarized a few of the leading paragraphs of the report of the Special Committee on Cosmic Terrestrial Relationships, which is printed in full as Appendix C.

Chairman Thom of the Special Committee on Exhibits reported that, at the request of the American Association for the Advancement of Science, the model of the basement-surface of eastern United States and other exhibits on display in 1939 were again shown in Philadelphia during the Christmas holidays. He stated that copies of the exhibits originally prepared for the Washington Assembly in 1939 [Trans. Amer. Geophys. Union 1940, pp. 739-741, 1940] have been sold to many interested parties among universities and oil companies and that he believed the original outlay on this project has been recaptured. He recommended the termination of the Committee since the material is now out of date and the work of the Committee is essentially complete. The Committee was discharged with thanks.

Chairman Macelwane of the Special Committee on Repository for Fundamental Geophysical Data stated that his Committee had not met and that individual members have been working by themselves as well as possible. He indicated that the program is, of necessity, a long-range one and that we have to be patient for results.

Chairman Lowdermilk of the Special Finance Committee told the meeting that there was no reason to change the report of his Committee from last year as to the needs of the Union and as to recommendations passed at that time for supplying those needs [Trans. Amer. Geophys. Union 1940, pp. 742-743, 1940]. However, he stressed one item which indicated the activities of the Committee through the year, namely, the negotiations which had been carried out attempting to get subsidies to tide the publication of the Transactions for several years. Dr. Lowdermilk continued as follows: "It is not likely that it will be possible to subsidize the Transactions for two years or so until we can catch up with the needs by increased membership, etc. Our most pressing need is for an editor who will take the burden of the Transactions from Dr. Fleming's shoulders. This is becoming more and more pressing as time goes on in view of the enlarged number of pages in the Transactions--over 1,150 pages (equivalent to about 1,700 pages in usual printed form) in the Transactions of 1940, or approximately 100 pages per month if placed on a monthly basis. Judging from the papers that have been and are being presented at the Twenty-Second Annual Meeting, I suspect that the pages will run considerably more. What are we going to do about this? One way is to increase our membership, and incidentally I was able to get five new members without half trying during this session. There is a keen interest in our Transactions. It is probably the principal publication on geophysics in the world today, and is greatly in demand in foreign countries. During the past year, sales amounted to over $2,000 apart from distribution to our own members. There is a demand for this publication of the Union and also a demand to give people an opportunity to become members. Our Membership Committee has been working on that problem in a fine way. We cannot report at present on the matter of a subsidy but hope something can be developed in that direction as soon as possible in supplying an editor for the Transactions who will be able to carry this load and help build up the interests of the Union."

Chairman L. H. Adams of the Special Committee on Award of the William Bowie Medal reported that J. A. Fleming was nominated by the Committee and that the third award of the Bowie Medal was made to him on the occasion of evening General Assembly for the presentation of the presidential address, April 30, by President Field [see pp. 234-235].

Chairman Fleming of the Special Committee on Revolving Funds reported that the idea behind the appointment of this Committee was that certain funds might be set aside for special purposes, for example, preparation of exhibits to be sold, any profits therefrom to be returned to this special fund. He further stated that the Committee was unanimous in the feeling that, until the Union's membership is increased sufficiently to warrant the full-time services of a secretary whose business will be to promote the Union and its publications, it would be rather unwise to set aside any funds at present since the Union's funds are none too large. Upon its request, the Committee was discharged with thanks.

The Committee on Resolutions [J. Marble (Chairman), N. H. Heck, and O. W. Torreson] then submitted through Chairman Marble the following report and three resolutions, which were adopted as a whole upon motion:

"The Committee wishes to report that three resolutions given below were received from the various Sections and Committees of the Union. Such changes and alterations in the resolutions as were thought desirable by this Committee, except for minor changes in grammar, have been made only after consultation with and approval by the person who submitted the resolution. This Committee knows of no further resolutions to come before the Union for consideration at the present time and thanks those persons who submitted resolutions for their cooperation."

Resolutions

(1) RESOLUTION ON MORE ADEQUATE METEOROLOGICAL BIBLIOGRAPHIC AND ABSTRACT SERVICE (proposed by the Section of Meteorology)

WHEREAS, There is a lack of an adequate meteorological bibliographic and abstract service, covering the foreign and domestic literature, which service is essential for the furtherance of research, therefore be it

RESOLVED, That the various meteorological institutions of the United States cooperate to provide more adequate bibliographic service.

(2) RESOLUTION ON RADIO TIME-SIGNAL SERVICE MAINTAINED BY THE UNITED STATES NAVAL OBSERVATORY AND THE NAVAL COMMUNICATION SERVICE [proposed by the Committee on Time-Signals of the Section of Seismology (H. Landsberg, Chairman, H. E. McComb, and E. L. Perry)]

WHEREAS, The science of seismology and the operation of seismological stations have a vital need of an accurate time-service, therefore be it

RESOLVED, That the American Geophysical Union, and in particular the Section of Seismology, again express their gratification for the radio time-signal service maintained by the United States Naval Observatory and the Naval Communication Service, which signal-service has been of great aid in seismology and other branches of geophysics, and be it further

RESOLVED, That copies of this resolution be sent to the Superintendent of the United States Naval Observatory, the Director of the Naval Communication Service, and the Secretary of the Navy.

(3) RESOLUTION OF THANKS FOR FACILITIES EXTENDED TO THE TWENTY-SECOND ANNUAL MEETING OF THE AMERICAN GEOPHYSICAL UNION (proposed by the Committee on Meetings)

BE IT RESOLVED, That the General Secretary of the American Geophysical Union be instructed to extend the heartiest thanks of the Union to Dr. Bush and Mr. Gilbert of the Carnegie Institution of Washington for the use of Elihu Root Hall for the General Assembly of the Union on April 30, 1941, and to the National Botanical Gardens for the flowers supplied for the meeting in Elihu Root Hall on April 30, 1941.

In addition to these three resolutions, it was voted by the meeting that the General Secretary send the thanks of the Union to the proper person for the use of the Departmental Auditorium.

Elections

Chairman Garner presented a report for the Committee on Nominations nominating W. C. Lowdermilk and L. H. Adams for President and Vice-President of the Union, respectively, for three years from July 1, 1941. There being no other nominations from the floor, W. C. Lowdermilk and L. H. Adams were unanimously elected President and Vice-President of the Union, respectively, for three years from July 1, 1941. Discussion of this Committee's recommendation [see Appendix D] of a possible change in the term of officers resulted in a vote that a committee be appointed to study this whole question and that action be taken during the next administration.

The General Secretary reported the election of the following officers of Sections for three years from July 1, 1941:

Geodesy--President, R. M. Wilson; Vice-President, C. R. Longwell (the three-year term of Secretary W. D. Sutcliffe continues through June 1943)
Seismology--President, H. E. McComb; Vice-President, V. C. Stechschulte (the three-year term of Secretary Frank Neumann continues through June 1942)
Meteorology--President, C. W. Thornthwaite; Vice-President, C.-G. Rossby; Secretary, H. D. Harradon
Terrestrial Magnetism and Electricity--President, E. A. Eckhardt; Vice-President, H. F. Johnston; Secretary, J. Wallace Joyce
Oceanography--President, P. C. Whitney; Vice-President, H. U. Sverdrup; Secretary, Waldo L. Schmitt
Volcanology--President, A. F. Buddington; Vice-President, J. F. Schairer; Secretary, J. S. Vhay
Hydrology--No elections
Tectonophysics--No elections

New business

The General Secretary read a letter dated May 1, 1941, from A. C. Swinnerton, Secretary of Section E of the American Association for the Advancement of Science, inviting the participation of the American Geophysical Union in at least one of its sessions at the Dallas Meeting in December, 1941, and particularly in its symposium on ground-water problems. It was moved and carried that a letter be written to the Secretary of Section E of the Association advising him that the American Geophysical Union would be glad to participate and to print the papers which may be presented at any such joint meeting in its Transactions.

The meeting adjourned at 1:10 p.m.

SCIENTIFIC SESSION

The scientific session, at which W. C. Lowdermilk presided, began at 2:38 p.m. with 93 members and guests present [see Appendix A] and was devoted to a symposium on dynamics of land erosion as printed in these Transactions [pp. 236-320].

The meeting adjourned at 5:18 p.m.

The minutes of the meetings of the Sections of the American Geophysical Union, April 30 to May 3, 1941, are given in attached Appendix E.

(Signed) Jno. A. Fleming, General Secretary,
American Geophysical Union

APPENDIX A--RECORD OF 479 MEMBERS AND GUESTS WHO REGISTERED ATTENDANCE AT THE GENERAL ASSEMBLY OF THE UNION AND AT SESSIONS OF ITS SECTIONS, TWENTY-SECOND ANNUAL MEETING, APRIL 30-MAY 3, 1941

(Total number in attendance was considerably in excess of those registered)

(1 = Business session of General Assembly; 2 = Scientific session of General Assembly; a = Geodesy; b = Seismology; c = Meteorology; d = Terrestrial Magnetism and Electricity; e = Oceanography; f = Volcanology; g = Hydrology; and h = Tectonophysics)

Adams, L. H. (1,f,h)
Adams, O. S. (a)
Adams, T. C. (1,g)
Adkinson, J. A. (e)
Affleck, James (a,d,f)
Allen, Charles T. (a)
Arctowski, H. (c,e,g)
Avers, H. G. (1,a)
Avet, Ch. (1)

Back, N. A. (g)
Bailey, Reed W. (2,g)
Bainbridge, W. H. (a)
Baker, A. A. (2,e,h)
Baldwin, D. H. (a)
Balsam, Ella (d,f)
Balsley, J. B. (h)
Barck, W. F. (a)
Barnes, B. A. (g)
Barnes, Bertram S. (g)
Bazzoni, C. B. (h)
Beckensbie, Celia (c)
Beij, K. H. (1,g)
Benfell, Vincent S. (a)
Benfield, A. E. (h)
Bent, A. E. (c)
Benton, B. M. (c)
Bernard, Merrill (1,g)
Betz, F. (2,a)
Birch, Francis (b)
Blair, Wm. R. (c)
Blake, Archie (b)
Blumenstoch, George (g)
Bodle, R. R. (b,c)
Bonsteel, J. A. (2,g)
Bourquard, E. H. (g)
Bowen, N. L. (f)
Bowie, John, Jr. (a)
Braaten, N. F. (a)
Bradford, D. C. (c)
Bradford, Gershom (e)
Brands, M. D. (1,g)
Brandt, A. E. (g)
Brannock, W. W. (g)
Brater, E. F. (2,g)

Brooks, C. F. (c)
Brooks, Harvey (h)
Brown, Carl B. (2,g)
Brown, Russell H. (g)
Brundage, F. H. (a)
Bryan, G. S. (e)
Bucher, Walter H. (b)
Buie, B. F. (f)
Burbank, W. S. (2,f)
Burhoe, Ralph W. (c)
Burlew, J. S. (f)
Butterfield, A. D. (a)
Byers, Alan C. (2,g)

Cady, R. C. (g)
Caldwell, Frank E. (c)
Callaway, E. B. (e)
Campbell, Joel B. (d)
Cantwell, David W. (2)
Capello, J. J. (1,2,b,d,e)
Cardwell, D. J. (g)
Carstensen, L. (c)
Chayes, F. (f)
Cheney, W. L. (d)
Chick, A. C. (b,c,g)
Choun, H. F. (c,g)
Church, P. E. (c,e,g)
Claire, C. N. (a)
Clapp, V. O. (c)
Clayton, H. H. (c)
Clifford, Charles J. (a)
Clinite, R. G. (a)
Clough, H. W. (c)
Cochran, A. L. (1,g)
Colbert, L. O. (e)
Collins, E. B. (e)
Collins, W. D. (g)
Collins, W. T. (1,g)
Colson, D. V. (c)
Conover, L. F. (c)
Cook, H. L. (g)
Cooper, H. H., Jr. (g)
Corwin, L. B. (c)
Creskoff, Jacob J. (b)
Cressey, George B. (2)
Crosby, I. B. (1,g)
Cross, Wm. P. (g)
Cubbon, M. H. (g)

Darrow, W. E. (2)
Davenport, R. W. (1,2,g)
Davis, G. L. (e,f,h)
Davis, W. E. (1,2,g)
De Fabritis, L. L. (2,g)
Delaney, John P., S.J. (b)
Dellinger, J. H. (d)
Demorest, Max (2,a,g)
Demorest, Rebecca H. (a)
Dermody, Rosemary (d)
Desakorn, S. (e)
Diebold, C. H. (1,2,g)
Dimitrijeird, W. J. (c)
Disney, L. P. (e)
Dobrin, Milton (a,d,f)
Dobson, G. C. (2,g)
Dorsey, H. G. (c,e)
Drane, B. S. (1)
Drisko, J. B. (1,g)
Duerksen, J. A. (a,f)
Duncan, D. C. (h)
Dyck, H. D. (c,g)

Eargle, D. H. (g)
Eaton, H. N. (g)
Eckhardt, E. A. (1,d)
Edlefsen, N. E. (1,g)
Einstein, H. A. (2,g)
Eisenlohr, Wm. S., Jr. (g)
Ellingwood, C. F. (a)
England, J. (a)
English, R. A. J. (e)
Escoffier, Francis F. (2,e,g)

Falciani, R. A. (a)
Farnham, F. C. (1,a,b,d)
Ferguson, E. E. (2,g)
Ferris, J. G. (g)
Fewell, J. M. (c)
Fidler, J. C. (c)
Fiedler, A. G. (g)
Field, R. M. (1,2,b,d,e,f)
Field, Wm. O., Jr. (g)
Finley, R. B. (a)
Fishel, O. C. (g)
Flaxman, E. W. (2)
Fleischer, M. (f)
Fleming, J. A. (1,2,a,c,d,e)
Fogel, E. H. (d)
Foshag, W. (f)
Frank, Bernard (g)
Franklin, W. R. (c)
Fraser, D. M. (f)
French, O. B. (a)

Galtsoff, Paul S. (e)
Garner, C. L. (1,a,d,e)
Gartlein, C. W. (d)
Gartlein, Mrs. C. W. (d)
Geyer, R. A. (a)
Gilcrest, B. R. (1,g)
Gilliland, T. R. (d)
Gish, O. H. (1,2,c,d,f,h)
Glass, Jewell J. (f)
Goddard, E. N. (f)
Goldthwaite, Richard P. (b)
Goodman, Clark (h)
Goodridge, R. S. (1,g)
Goranson, R. W. (f)
Gottschalk, L. C. (g)
Gottshall, Drusilla (d)
Graton, L. C. (f,h)
Graves, G. Van A. (1,e)
Green, J. W. (d)
Greig, J. W. (f)
Griggs, A. L. (c)
Griggs, D. T. (2,h)
Gross, G. G. (b)
Grover, N. C. (1,2,g)
Gumbel, E. J. (g)
Gunn, Ross (d)
Gutenberg, B. (1,2,b,c,d,f,h)
Guthe, O. E. (2,g)
Guyton, W. F. (g)

Haase, B. J. (d)
Hafstad, K. C. (2,c,g)
Hagen, N. R. (c)
Haight, F. J. (e)
Halstead, M. H. (c)
Hammer, Sigmund (a,d,f)
Harmantos, Louis (c)
Harradon, H. D. (1,2,c,d,e,h)
Harris, N. S. (a)
Harrold, L. L. (2,g)
Hartley, Henry (e)
Hartman, G. F. (g)
Harvill, Clyde R. (g)
Hathaway, G. A. (1,g)
Heck, N. H. (1,2,b,d)
Hemple, H. W. (a)
Hendrix, W. C. (d)
Hersey, J. B. (a,f)
Hershberger, John (b,d,f)
Hertzler, R. A. (2,g)
Hess, H. H. (1,e,f)
Hill, Jesse (a)
Hobbs, Harold W. (2,g)
Holzman, Benj. (c)
Horner, W. W. (2,g)
Horton, A. H. (g)
Horton, R. E. (2,g)
Howard, C. S. (g)
Howe, E. D. (d,f)
Howe, H. H. (d)
Hoyt, W. G. (2,g)
Huff, T. F. (d)
Hulburt, E. O. (c,d)
Humphreys, W. J. (c)
Hunter, H. C. (c)
Hursh, C. R. (g)
Hurwitz, L. (d)
Hutt, J. B. (e)

Ingersoll, H. B. (g)
Ingerson, Earl (f)
Ippen, A. T. (2,g)
Ireland, H. A. (g)
Iselin, C. O. (e)
Izzard, C. F. (2,g)

Jacob, C. E. (g)
Jarvis, C. S. (1,2,g)
Johnson, J. W. (2,g)
Johnston, H. F. (d,f)
Johnston, W. D., Jr. (f)
Jones, B. E. (g)
Jones, Lewis O. (g)
Jordan, Clarence R. (c)
Joyce, J. W. (d)
Judson, L. V. (1,a)

Kalinske, A. A. (1,g)
Kazmann, R. G. (g)
Keith, Arthur (2,b)
Kellar, John G. (e)
Kennard, R. B. (g)
Keppel, David (f)
Keulegan, G. H. (g)

King, Albert L. (g)
Knapp, David G. (d)
Knapp, R. T. (1,g)
Kohler, J. P. (c)
Korff, S. A. (d)
Korff, Mrs. S. A. (d)
Koschmann, A. H. (f)
Krasnow, S. (h)
Krimgold, D. B. (2,g)

Lambert, W. D. (2,a,b)
Lane, A. C. (2,b,f,g,h)
Lane, E. W. (1,2,g)
Lange, Isabelle (d,f)
Lansberg, H. (b,c)
Larsen, E. S. (f)
Lassen, Leon (g)
Laws, J. Otis (2,g)
Lay, E. T. (c)
Leggette, R. M. (g)
Lennahan, C. M. (c)
Light, Phillip (c,g)
Linehan, Daniel (b)
Linsley, R. K. (g)
Loeffler, O. H. (f)
Lohman, K. E. (2)
Lohman, S. W. (g)
Lorz, J. G. (d)
Love, S. K. (2,g)
Lovering, T. S. (f)
Lowdermilk, W. C. (1,2,c,g)
Ludy, A. K. (1,2,b,d)
Lynch, Joseph (b)
Lynch, William A. (b)
Lyons, W. S. (a)

MacCarthy, S. R. (2)
Macelwane, J. B. (1,2,b,c,d)
Magnuson, N. C. (g)
Maher, J. C. (g)
Malina, Frank J. (2,g)
Mansfield, G. R. (2)
Marble, Adelaide H. (2,f,h)
Marble, J. P. (1,2,f,h)
Maris, H. B. (c,d)
Marsh, L. E. (1,g)
Martin, Lawrence (b,e,g)
Mason, John F. (a,h)
Mason, M. A. (2)
Mathisson, J. C. (e)
Matthes, F. E. (g)
Matthes, G. H. (1,g)
Mattice, W. A. (c)
Mauchly, J. W. (c)
Mavis, F. T. (g)
McCall, A. G. (1,2,c,g)
McComb, H. E. (1,b,d)
McCombs, C. E. (a)
McDonald, W. F. (c)
McGee, B. C. (a)
McNish, A. G. (1,2,d,f,h)
Meade, B. K. (a)
Mears, A. H. (c)
Medina, Guillermo (e)
Meinzer, O. E. (1,g)
Merriam, Carroll F. (a,g)
Middleton, H. E. (c,g)
Middleton, W. E. K. (c)
Miles, J. R. (c)
Milton, Charles (f)
Mitchell, C. L. (c)
Mitchell, D. L. (a)
Mitchell, H. C. (a)
Moore, B. H. (c)
Morey, G. W. (f)
Morgan, A. M. (g)
Mueller, John F. (2,a)
Munns, E. N. (2)
Murray, Harold W. (e)
Murto, H. C. (2,g)
Musgrave, G. W. (1,2,g)
Myers, A. J. (c)

Nelson, W. A. (a,e)
Neuner, C. G., S.J. (b)
Newlin, D. B. (a)
Nichols, R. L. (f)
Nicoson, K. S. (c)
Nolan, T. B. (h)
Norquest, K. S. (c)
Norton, Horace W. (c)

Olmstead, L. B. (c,g)
Olson, J. C. (f)
Osborn, E. F. (f,h)
Ould, R. S. (d)
Owen, J. C. (2,g)

Page, B. L. (a)
Palmer, W. M. (a)
Parker, G. G. (g)
Parkin, E. J. (a)
Pate, F. C. (c)
Patterson, G. W. (2,g)
Pawling, Jesse (a,c)
Pecora, Wm. T. (f)
Pedersen, Clarence (g)
Pekeris, C. L. (c,e,h)
Peoples, J. W. (f)
Percy, M. F. (a)
Perry, E. L. (2,b)
Petretic, G. J. (g)
Pietsch, W. H. (g)
Pillsbury, A. F. (1,g)
Pinckney, Harold W. (b)
Piper, A. M. (b,g)
Poling, A. C. (a)
Powell, R. W. (g)
Powers, E. R. (b)
Puffer, Shirley (d)

Raab, Emil A. P. (c)
Rappleye, H. S. (1,a)
Raynsford, G. M. (a)
Reed, E. W. (g)
Rekate, G. H. (a)
Revell, R. W. (g)
Rice, D. A. (a)
Riesbol, H. S. (g)
Riley, W. G. (c)
Risher, C. L. (c)
Ritchie, D. C. (a,e)
Robbins, Don R. (c)
Robinson, T. W. (g)
Roes, J. S. (d)
Rome, Elisabeth (e)
Rosa, J. M. (g)
Rose, C. S. (f)
Ross, C. S. (f)
Rossby, C.-G. (c)
Rubey, W. W. (2,f,g)
Russell, Richard J. (2,c,g)

Saltsman, C. J. (c)
Samuels, L. T. (c)
Schaefer, E. J. (g)
Schairer, J. F. (f,h)
Schiff, Leonard (2,g)
Schmidt, Albert (d)
Schmitt, A. R. (b)
Schneible, Douglas (a)
Scofield, C. S. (g)
Scott, W. E. (2,c,d,e,h)
Shalowitz, A. L. (e)
Shand, S. J. (f)
Shanklin, G. R. (g)
Sharpe, J. A. (b)
Sherman, K. L. (1,2,c,d,h)
Sherman, L. K. (1,g)
Shilson, J. S. (c)
Shmidl, L. E. (a)
Shofnos, William (e)
Showalter, A. K. (c)
Sims, I. H. (2)
Skeels, D. C. (a,d,f,h)
Slayton, C. C. (e)
Small, J. B. (a)
Smith, B. A. (c)
Smith, Paul A. (c,e)
Smith, W. E. (1,2,c,g)
Smith, W. O. (g)
Snyder, F. F. (1,g)
Sohon, F. W. (b)
Speert, J. L. (a)
Spencer, A. C. (f)
Spencer, John N. (g)
Spilhaus, A. F. (c,e)
Stechschulte, V. C. (2,b,d)
Steiner, W. F. (d)
Stetson, H. T. (1,a,e)
Stirni, A. R. (a)
Stone, R. G. (c)
Straub, L. G. (1,2,g)
Stringfield, V. T. (g)
Sulpowspi, Eugene (c)
Sutcliffe, W. D. (a)
Sverdrup, H. U. (1,c,d,e)
Swainson, O. W. (b,d)
Sweet, J. S. (c,g)
Swenson, Bennett (c)
Swick, C. H. (1,2,a,d,f,h)
Swinnerton, A. C. (2,c,g)
Sykes, Lloyd (c)

Tannehill, I. R. (c)
Thayer, T. P. (f)
Theis, C. V. (g)
Thom, H. C. S. (1,g)

Thom, W. T., Jr. (1,2,a,h)
Thomas, H. E. (b,g)
Thompson, D. G. (b,g)
Thone, Frank (b)
Thornthwaite, C. W. (2,c,g)
Tibbott, E. W. (a)
Timberman, C. W. (c,g)
Todd, C. C. (e)
Torreson, O. W. (1,2)
Tracey, J. J., Jr. (2)
Trask, Parker D. (e)
Tuckerman, Bryant (2,d,f,h)
Tunell, G. (f)
Turner, S. F. (g)
Tweto, Ogden (f)

Underwood, P. H. (2,h)
Urry, W. D. (h)

Vacquier, V. (d)
Vanoni, Vito A. (2,g)
Van Orstrand, C. E. (a,h)
Van Thullenar, C. F. (c)
Vaughan, T. W. (1,e)
Vestine, E. H. (d,f)

Wait, G. R. (c,d)
Waite, H. A. (g)
Wallis, W. F. (b,c,d)
Warren, M. A. (g)
Watson, Robert J. (a,d,f,h)
Watt, William G. (e)
Watts, C. B. (a)
Weber, J. L. (2)
Wells, H. W. (d)
Wenner, F. (b)
Wenzel, L. K. (g)
Whitcroft, T. H. (e)
White, W. N. (g)
Whitten, C. A. (a,f)
Williams, Earl L. (2)
Williams, G. R. (g)
Williamson, R. O. (a)
Willis, J. E. (a)
Wilson, J. T. (2,b)
Wilson, R. H., Jr. (a)
Wilson, R. M. (1,2,a)
Wilson, R. N. (1,g)
Windes, S. L. (b)
Wolfe, Peter E. (2)
Woodring, W. P. (2,h)
Woolard, E. W. (c)
Woolhiser, J. E. (e)
Woollard, G. P. (a,d,f,h)
Wright, F. E. (1,2,a,e,h)
Wulf, Oliver R. (c)

Zetler, Bernard (e)
Zies, E. G. (2,f)
Zwerner, G. A. (g)

APPENDIX B--REPORT OF THE GENERAL SECRETARY OF THE AMERICAN GEOPHYSICAL UNION TO THE GENERAL ASSEMBLY, TWENTY-SECOND ANNUAL MEETING, MAY 2, 1941

Minutes of the Twenty-First Annual Meeting held April 26, 1940, were printed in the Transactions of 1940 [pp. 723-749] and were distributed to all members of the Union and to authors of papers presented at the meeting. No suggestions for changes or corrections have been received.

In accordance with instructions, the various resolutions adopted at the General Assembly of the Union at the Twenty-First Annual Meeting were transmitted to the various organizations and individuals concerned. Acknowledgments received from the Acting Secretary of Commerce, the Director of the United States Coast and Geodetic Survey, the Hydrographer of the Navy, the Secretary of the Navy, and the President of St. Louis University all state that every effort would be made to realize the objects of the several resolutions.

Eight members of the Union have died since the last annual meeting: William Bowie, August 28, 1940, affiliated with the Sections of Geodesy, Oceanography, and Tectonophysics; E. B. Calvert, July 9, 1940, affiliated with the Sections of Meteorology and Oceanography; B. C. Freeman, August 25, 1940, affiliated with the Sections of Volcanology, Hydrology, and Tectonophysics; Benjamin C. Kadel, March 30, 1940, affiliated with the Section of Meteorology; Larry F. Page, June 10, 1940, affiliated with the Section of Meteorology; W. A. Tarr, July 28, 1940, affiliated with the Sections of Seismology, Meteorology, Oceanography, Volcanology, and Hydrology; John B. Hawley, January 9, 1941, affiliated with the Section of Hydrology; John P. Dean, April 9, 1941, affiliated with the Sections of Geodesy, Seismology, Meteorology, Terrestrial Magnetism and Electricity, Hydrology, and Tectonophysics.

The total membership of the Union May 2, 1941, is 1,327--a net gain of 63 during the past year. The Membership Committee is now making plans for an intensive drive for new members through distribution to qualified persons of a circular regarding the Union's purposes and activities.

A list of members and officers of the Union as of August 1, 1940, was completed in an edition of 2,000 and copies were distributed to all members. Unfortunately, one serious error has been noted in this list, namely, in the officers of the Section of Hydrology, the tenures on page 27 being from 1939 to 1942 for all three and the Vice-President being M. P. O'Brien instead of J. E. Church. Corresponding corrections are, of course, required in the list of members of the Section of Hydrology on pages 36, 37, and 38.

The Executive Committee held two meetings since the last report (November 16, 1940, and March 28, 1941). Copies of the minutes of these meetings were distributed to members of the Committee and to officers of the Sections.

Arrangements were made for the Twenty-Second Annual Meetings of the Union and of its Sections in Washington April 30, May 1, 2, and 3, 1941, the program for the scientific sessions, including over 125 papers and progress-reports.

Following instructions by the Executive Committee, the following Special Committees have been appointed since the Twenty-First Annual Meeting: To Study and Report Whether Revolving Funds Should be Designated--J. A. Fleming (Chairman), R. M. Field, and H. D. Harradon; On National Welfare and Related Functions--R. M. Field (Chairman), W. C. Lowdermilk, and J. A. Fleming; On Loans and Equipment--H. D. Harradon (Chairman), J. A. Fleming (Secretary), W. T. Thom, M. Ewing, H. T. Stetson, and W. C. Lowdermilk. This last Committee was discharged after it had effectively served its purpose.

The Transactions of 1940 of the Union were edited and prepared for publication in four parts: Part I (144 pages) giving the proceedings of the joint regional meeting of the Section of Hydrology and the Western Interstate Snow-Survey Conference at Stanford University in January, 1940; Part II (643 pages) containing the complete proceedings of the Twenty-First Annual Meeting; Part III (280 pages) containing the symposium presented at the Richmond meeting of the American Association for the Advancement of Science in December, 1938, and the proceedings of the joint regional meeting of the Section of Hydrology and the Western Interstate Snow-Survey Conference at Seattle in June, 1940; and Part IV (84 pages) containing the papers presented in the two symposia at the Columbus meeting of the American Association for the Advancement of Science in December, 1939. Thus the Transactions of 1940 contain a total of 1,151 pages. The regular edition of each part of the Transactions is 2,000, but in addition 2,600 each of Parts I and III were ordered for distribution to the members of the Western Interstate Snow-Survey Conference and of the International Commission of Snow and Glaciers; 300 additional copies were ordered of Part IV to meet the demand anticipated on the part of members of the Mathematical Association of America.

In view of the success attending the many regional meetings sponsored by the Section of Hydrology, the Executive Committee of the Union has recommended to the officers of the several other Sections the consideration of whether such regional meetings as units or jointly with other Sections might not be profitable and helpful in advancing the various research fields of Geophysics. The Union's help in sponsoring the Western Interstate Snow-Survey Conferences of past years has doubtless been a factor in the great increase in interest in snow-surveying throughout the United States. Thus, in addition to the Western Interstate Snow-Survey Conference there have recently been established an Eastern States Snow-Survey Conference and the Great Lakes Snow-Survey Conference.

Under the general direction of Chairman F. J. Veihmeyer of the South Pacific Area, a regional meeting of the Section of Hydrology was held in Sacramento, California, January 16 to 18, 1941, with Harold Conkling as Chairman of the meeting. The Western Interstate Snow-Survey Conference also held a meeting in Sacramento on January 16, 1941, to hear reports and papers. The Executive Committee has authorized publication of reports and papers presented at these meetings and master-copy for printing is already one-half completed.

The Bibliography of Hydrology, United States of America, for the year 1939 (86 pages) was prepared in an edition of 1,000 from manuscript prepared by the Secretary of the Section of Hydrology and Miss Mary O. Soroka, Chairman of the Committee on the Bibliography. Copies are being held as required for the Secretary of the International Association of Scientific Hydrology and all but a few of the remainder have been sold at 50 cents each.

J. A. Fleming was reappointed a member of the Division of Foreign Relations of the National Research Council for the three-year period ending June 30, 1943. The General Secretary has submitted an annual report to this Division relating to the work of the International Union of Geodesy and Geophysics and the American Geophysical Union.

The National Research Council has included in its estimates for the fiscal year ending June 30, 1942, a grant of $400 to the Union.

The report of the Auditing Committee for the calendar year 1940 showed that receipts ($16,206.51 including balance January 1, 1940, of $6,968.02) and disbursements ($9,694.54 including $3,381.81 for Transactions of 1940) correspond exactly with the General Secretary's summary for that period.

There has been continued cooperation by the Union with the Division of Physical Sciences of the National Research Council in the preparation of special bulletins on geophysical methods, instruments, results, etc. The special volume on hydrology in the series "Physics of the Earth" of the Council has progressed well.

The Director of the National Roster of Scientific and Specialized Personnel has distributed tO 2,000 addresses supplied by the American Geophysical Union a questionnaire on geophysics. It is hoped that the information received in answer to this questionnaire will be found useful to various agencies of the Government, including the United States Civil Service Commission, in the selection of trained geophysicists.

A complete account of the Washington Assembly of the International Union was prepared and published in Science (May 10, 1940). This report, together with the addresses at the opening assembly of the International Union (Science, October 13, 1939) was reprinted under one cover and distributed to all members of the Union.

The sale continues of black and white copies of the special-exhibit maps prepared by the Union for the Washington Assembly of the International Union of Geodesy and Geophysics. The Special Committee on Exhibits prepared an exhibit booth in connection with the Philadelphia meeting of the American Association for the Advancement of Science.

The contribution of the United States for the calendar year 1939 as an adhering member of the International Union of Geodesy and Geophysics, namely, $3,920.40, after considerable delay because of obtaining the necessary papers and endorsements from General Secretary Winterbotham in England and the regulations regarding handling of funds in England, has now been deposited with the Riggs National Bank of Washington, D. C., in the name of the International Union of Geodesy and Geophysics by J. A. Fleming. After payment of amounts due the American Geophysical Union for advances made to the various International Associations during the Washington Assembly there is now a balance of $2,835.82. So far as possible, correspondence has been maintained with the officers of the International Union. A voucher has been signed by J. A. Fleming as Vice-President of the International Union for the contribution of the United States to that body for the calendar year 1940 in a total of $3,920.40. With the explanation and supporting evidence of the actions taken at the Washington Assembly, it is hoped that payment will be received for deposit to the account of the International Union in the Riggs Bank. In this connection, a circular letter dated October 12, 1940, was received from General Secretary Winterbotham to the effect that, since the International Union is no longer in a position to keep in touch with many of its original members because of present circumstances, further subscriptions will not be asked for until the return of peace, when it is felt that the scientific, administrative, and financial measures necessary for the reconstruction of the Union will prove an easy task. Action has already been taken by the Congress for payment of the quota of the United States for 1941. When a General Assembly is next in a position to review the finances of the International Union, it will have before it a statement dealing with the debt to, or credit with, the Union of each adhering country.

The 375 copies of the Transactions of the Washington Assembly (1939) of the International Association of Physical Oceanography have now been received without cost other than that of entry and freight. These have been distributed in the United States to persons who had made request for them. Two hundred and eighty copies of a promised 300 of the Transactions of the Washington Assembly (1939) of the Association of Terrestrial Magnetism and Electricity have been received and are being distributed. Several copies of the Transactions of the Washington Assembly (1939) of the Association of Seismology have been received but it has not been possible for the supply of copies requested by the Union to be forwarded from France. Advice has been received from Secretary Winterbotham of the International Union that 400 printed copies of the General Transactions of the Washington Assembly (1939) are being forwarded for distribution by the Union. In March several copies were received from Norway of the Transactions of the Washington Assembly (1939) of the Association of Meteorology. There remain to be published therefore only the Transactions of the Washington Assembly of the Associations of Volcanology, Scientific Hydrology, and Geodesy.

Our Union's activities are an ever-increasing factor nationally and internationally in the advance of developments in the Earth sciences and improved application of knowledge therefrom to human economy and welfare.

(Signed) J. A. Fleming, General Secretary,
American Geophysical Union

APPENDIX C--REPORT OF SPECIAL COMMITTEE ON COSMIC TERRESTRIAL RELATIONSHIPS

Members of the Special Committee on Cosmic Terrestrial Relationships have reported progress in special fields of investigation pertinent to the work of the Committee.

Professor Brooks reports that the continued measurements of ultra-violet radiation with the Coblentz cell and with a dosimeter have been continued on Mount Washington. The records cover an interval of over one-half year with the cell and a period of four years with the dosimeter. Records of solar radiation at normal incidence have been maintained at Blue Hill Observatory for a total now of eight years, with a Schott filter dividing the spectrum into three parts. Dr. Brooks called attention to the fact that the headquarters of the solar-radiation work of the Weather Bureau has been transferred during the past year from Washington to the Blue Hill Observatory.

Studies in the variation of high-frequency transmission through the cooperation of Professor A. W. Friend have been continued at Blue Hill. Measurements of the intensity of reflected radio pulses from within the troposphere were recorded from October, 1939, to the end of 1940. With the cooperation of G. W. Pickard and others, experiments are being continued on wave-lengths shorter than 200 megacycles. The observations are being compared with meteorological data.

H. Helm Clayton has continued his studies of solar cycles and recurrences in meteorological and magnetic data. He finds that the period of solar rotation as indicated by the intervals between maxima and minima of spots varies with the latitude of the spots, but on the whole shows a persistent period averaging 27.26 days with maximum amplitude at the times of sunspot maxima. He also finds that the new measures of corpuscular radiation recorded at the seven magnetic observatories, including two of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and five of the United States Coast and Geodetic Survey, show statistically a lag between one and two days after maxima of relative sunspot-numbers just as do auroras. Like auroral displays, these numbers are clearly connected with outbreaks on the Sun from which clouds of electrified particles reach the Earth. For this reason their variation cannot be taken as a measure of short-period changes in solar activity. He finds, for example, that at a time of small sunspot-activity, as on March 30, 1941, there may be a marked increase in K_A-numbers coinciding with the appearance of a new group of small sunspots near the central area of the Sun. Thus, while there is evidently a close relation to solar activity, it is not correlated with activity over the entire solar surface.

Mr. Clayton finds a close relation between the mean atmospheric pressure at the latitude of 70° on the Earth and the day-to-day changes in the relative sunspot-numbers. The increase of pressure at latitude 70° coincides with a fall of pressure at latitudes below 45° so that with each change in solar activity there appears to be an oscillation of air-mass between low and high latitudes.

The ionospheric data from the National Bureau of Standards Radio Division under Dr. Dellinger has continued to prove of special value to the study of cosmic effects on the ionosphere. The standard-frequency wave on 5.00 megacycles almost continuously on the air has provided a new source of investigation of factors due to atmospheric and extra-terrestrial origin.

Dr. Ewing has been attached to the Woods Hole Oceanographic Institution for the investigation of problems of national defense.

Notable contributions on geomagnetism and atmospheric electricity have been made at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. These are comprehensively covered in the last report of the Director, Dr. Fleming. Analysis of accumulated data from this institution has shown significant geomagnetic relationships with solar and lunar effects, a high correlation being shown between a long series of magnetic data at Huancayo and the Zurich sunspot-numbers with a coefficient now in excess of 0.9. The addition of Mr. Berkner to our Committee has been of special value in problems touching ionospheric research.

Members of the Committee at the Naval Observatory have been helpful in supplying information concerning the necessary changes in the transmission of time-signals which have been of special use in a particular problem to be later mentioned, and in providing current solar data.

The United States Coast and Geodetic Survey, in cooperation with the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, has added materially to significant cosmic data by furnishing K-numbers and in carrying these back to 1937 so that a proper appraisal of their value may be made. The K-numbers are indices of magnetic activity on the basis of three-hour ranges and are now published weekly in the Bulletin of Cosmic Data by Science Service. These new indices offer wide possibilities in studies of cosmic terrestrial phenomena. Valuable magnetic information has been furnished various organizations investigating radio transmission-conditions. The value of routine magnetic data has been emphasized by Captain Heck as of increasing importance in view of the close association of magnetic disturbances with the field of radio communication. There has been close cooperation between the Survey and Dr. Kenrick in his ionospheric investigations in Puerto Rico, especially so since the information derived from the Magnetic Observatory is in the vicinity of San Juan. Through the courtesy of Captain Heck, a magnetic station was established in the autumn of 1940 at Needham, Massachusetts, on the grounds of the new laboratory for cosmic terrestrial research in affiliation with the Massachusetts Institute of Technology.

Dr. Hodgson of the Dominion Observatory at Ottawa reports that, while the demands of the Dominion are of necessity immediately related to the war, certain types of research pertinent to the work of this Special Committee have been temporarily deferred. The Observatory, however, has continued to collect seismic and other geophysical data that will be of service for analysis at a later date. While carrying forward the regular seismic service for Canada, some time has been available for the study of rock-bursts in the hard-rock levels of mines in northern Ontario.

Dr. Hulburt of the Naval Research Laboratory travelled to Brazil in the autumn of 1940 for observations during the total solar eclipse. While there was much interference by clouds during the eclipse itself, photometric observations during the Expedition's stay showed that the brightness of the zenith twilight sky for depression of the Sun from 0° to 13° below the horizon was essentially the same as that observed at temperate latitudes. This led to the conclusion that the temperature of the atmosphere during morning and evening twilight was about 218° absolute and constant with altitude for altitudes from 20 to 60 km.

Professor Kaplan of the University of California has reported for publication the results of spectroscopic studies of the afterglow in high-frequency discharge-tubes, obtaining the "forbidden" lines observed in auroras, indicating the presence of helium in the upper atmosphere.

Dr. Kenrick, reporting from Puerto Rico, has continued measurements of the field intensity of WBBM Chicago on 770 kc, as well as observations on station GLH London operating on a frequency of 13.54 megacycles. His investigations of ionospheric conditions now afford nearly a year's monthly means and show interesting departures from the results reported at Washington. He hopes that the work may be extended to include the computation of maximum usable frequencies from vertical-incidence data which are now being obtained. Observations of ultra-violet radiation have been continued through the cooperation of the School of Tropical Medicine of the University of Puerto Rico.

Dr. Landsberg of the Geophysical Laboratory of the Pennsylvania State College reports that he has continued exposure of the ultra-violet glass rods under various conditions, especially under filters in order to obtain data on the relative intensity of ultra-violet in the neighborhood of 3,600 to 3,900 Ångströms. Some studies have been made on the radiation from a snow-cover to space to obtain information concerning possible effects on the atmosphere. A series of measurements of Arago's point was made by Dr. Neuberger with the aim of determining the penetration of cosmic dust into the upper atmosphere.

Professor J. Q. Stewart has continued his investigations on the prediction of sunspottedness based on the four-parameter family of curves representing the general course of each outburst. His predicted mean yearly averages for 1939, 1940, and 1941 were 87, 61, and 28, respectively. The observed values for 1939 and 1940 were 88 and 68. It would appear from his prediction that the next minimum may be anticipated in 1944 or 1945.

Under the direction of Professor Thom of Princeton a survey has been undertaken of reliable geologic data relative to lateral shifts of parts of the Earth's crust which would appear to have some bearing on the ultimate question of small variations in the latitudes and longitudes of stations within these areas.

During the past year a substantial addition has been made to the cosmic terrestrial research laboratory at Needham. To the single-storied building with which work was started, a two-storied structure has been added, measuring 20 by 40 feet, and providing additional space for office and laboratory. An observing roof allows for solar recorders, and a basement provides adequate space for an instrument-shop. Measurements of field-intensities on WBBM Chicago on 770 kc have been continued with marked deficiencies in field-strengths again accompanying solar and magnetic disturbances. An additional field-strength recorder has been installed and is at present in continuous operation on the carrier-wave of the National Bureau of Standards standard-frequency broadcast at 5.00 megacycles. It is hoped that field-strength observations at this higher frequency may be of help in interpreting microvolt variations in terms of ionospheric changes since on this frequency the sky-wave is observable both day and night.

Through the cooperation of Selby Haar of New York, continuous records have been kept of the received intensity of the time-signals from the United States Naval Observatory on several frequencies. When allowance is made for a seasonal variation, the observed intensity of the Washington signal during the past three years has shown remarkable agreement with variations in solar activity. Apparatus for the systematic measurement of potential-gradient has recently been installed at the Needham Laboratory, and acknowledgment is due to the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for the loan of one of its ionium-collectors to be used in this connection.

At the request of Professor Rojansky of Union College, our field-strength data have been examined for any possible clue to increased ionization at the approach of Cunningham's Comet as a possible check to his theory of terrine and contra-terrine matter.

Emphasis has been made from time to time on the necessity for correcting field-strength data to an adopted value for the depression of the Sun below the horizon before comparisons can be made in a study of extra-terrestrial effects. It has been presumed that both the diurnal and seasonal factors in ionic concentration could be allowed for in this manner, since presumably such variations are dependent chiefly upon the exposure of the ionosphere to the ultra-violet radiation of the Sun. Examination of our data of the last ten years, however, reveals an annual variation after corrections for solar altitudes and declinations have been applied. A preliminary study indicates a maximum in May and a minimum in August, the explanation for which will involve further investigation.

An automatic device at Needham has been put into operation for exposing the ultra-violet special glass rods developed by Dr. Landsberg, so that one rod is exposed each day between 09^h and 17^h. The problem of insuring a continued supply of these glass rods has been taken up with the Bausch and Lomb Optical Company.

In spite of present conditions often seriously interrupting or delaying fundamental research on account of the urgent problems of national defense, the Special Committee on Cosmic Terrestrial Relationships has been able to make a considerable progress during the year. It is believed that emphasis should be placed upon the importance of continuing systematic observations already in progress, since the ultimate value of cosmic data is largely dependent upon the continuity of records. It is obvious that under present conditions many members of your Committee have been or are engaged in special fields of research allied to national defense of which further mention at this time would be inappropriate, but the nature of which may contribute ultimately to some of the basic research in which this Special Committee has its interests.

Massachusetts Institute of Technology,
Needham, Massachusetts

Harlan T. Stetson, Chairman,
Special Committee on Cosmic Terrestrial
Relationships, American Geophysical Union

APPENDIX D--SPECIAL REPORT OF COMMITTEE ON NOMINATIONS

The Committee on Nominations has given thorough study and consideration to the problem assigned to it. In order to do this, contacts have been made with various members of the Union to obtain a cross-section of opinion. In these discussions some have questioned whether the term of office for our President and Vice-President of three years is not too long and should be revised by some shorter period possibly with the provision that a certain number of successive reelections would be desirable.

It would seem that this question becomes more important when we consider the growth of the Union during the last two decades, the increasing importance of geophysical research as related to a vast number of national problems, as well as its international aspects. Therefore, it is the recommendation of this Committee that a study be made with regard to this and all related matters by an appropriate committee to be appointed by the President in order that such action as may be found desirable may be taken during the next administration. Of course, this will not in any way affect the terms of office of those who are to be elected to the offices of President and Vice-President for the three-year term beginning July 1, 1941.

C. L. Garner, Chairman, J. A. Fleming, and David T. Griggs

APPENDIX E-a-MINUTES OF THE ANNUAL MEETING OF 1941, SECTION OF GEODESY, AMERICAN GEOPHYSICAL UNION

The Meeting was held in the Lecture Room of the National Academy and Research Council Building, Washington, D. C., May 2, 1941. The Meeting was called to order by the President, C. H. Swick, at 9:03 a.m. The registered attendance was 80.

The President called attention to the fact that the minutes of the Twenty-First Annual Meeting held April 25, 1940, had been printed and sent out to the members and that no corrections had been received. The minutes were declared approved as printed and circulated.

The Secretary stated that he had no report and the President then asked if the Committee on Relation of Inch and Meter had a report. R. M. Wilson stated that the Committee had no report.

The President stated that no resolutions had been called to his attention and that no Resolutions Committee had been appointed.

The report of the Nominating Committee (L. V. Judson, Chairman, H. G. Avers, and C. B. Watts) was given by Mr. Judson. R. M. Wilson was nominated for President and C. R. Longwell for Vice-President, each for a three-year term beginning July 1, 1941. No nominations were made from the floor and it was moved and carried that the candidates selected by the Nominating Committee be elected.

The President then asked W. D. Lambert to make a brief report on the International Association of Geodesy. It is thought that Mr. Lambert's report will be of interest to members of the Section who were not present at the Meeting and his report will therefore be printed in the *Transactions* with the scientific papers.

The Section then proceeded to hear the papers on the scientific program as published in these *Transactions* [pp. 323-363]. There was active discussion of the papers as follows: That by John E. Willis by Stetson and Garner; that by C. J. Clifford by Wilson, Benfell, Thom, and Garner; that by G. P. Woollard by Skeels and Thom; that by W. F. Barck by Eckhardt; that by H. W. Hemple by Mitchell and Hammer; that by F. W. Hough, read by C. A. Whitten, by Hemple; that by Chinghai Li, read by P. H. Underwood, no discussion; that by J. B. Hersey by Skeels and Nelson; that by Sigmund Hammer and E. T. Heck by Skeels and Nelson.

There being no further business, the Meeting adjourned at 12:28 p.m.

Walter D. Sutcliffe, Secretary,
Section of Geodesy,
American Geophysical Union

APPENDIX E-b--MINUTES OF THE ANNUAL MEETING OF 1941, SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The meeting was called to order by the President, J. B. Macelwane, S.J., at 2:10 p.m., May 1, 1941, in the Lecture Room of the National Academy and Research Council Building, Washington, D. C. The registered attendance was 34. In the absence of the Secretary, the President appointed A. K. Ludy as Secretary pro tem. [For registered attendance, see Appendix A.]

The minutes of the previous Meeting having been published and no objections or corrections having been received, the President declared them approved.

The Nominating Committee [R. R. Bodle (Chairman), P. Byerly, H. Landsberg, and J. J. Lynch, S.J.] placed the following in nomination for the three-year term from July 1, 1941: For President, H. E. McComb; for Vice-President, V. C. Stechschulte, S.J. There being no other nominations, the Secretary was instructed to cast a unanimous ballot for these nominees.

The scientific papers were presented as published in these *Transactions* [pp. 367-394] and lively discussion followed each paper.

After discussion of a suggestion by R. M. Field, President of the Union, a motion was carried to refer to the Executive Committee of the Section all matters pertaining to the maintenance of seismological projects suffering because of the war in Europe, especially to keep up the publication of the *International Summary of Earthquakes* and also all matters pertaining to cooperation with the National Defense.

A resolution was adopted expressing appreciation to the Navy Department for the excellent schedule of precise time-signals originating at the United States Naval Observatory and broadcast by the Navy Department from its various radio stations [see p. 563].

The Meeting adjourned at 5:30 p.m.

A. K. Ludy, Secretary pro tem.,
Section of Seismology,
American Geophysical Union

APPENDIX E-b(1)--MINUTES OF THE SIXTEENTH ANNUAL MEETING OF THE EASTERN SECTION, SEISMOLOGICAL SOCIETY OF AMERICA, HELD AT GEORGETOWN UNIVERSITY, MAY 2, 1941, JOINTLY WITH THE SECTION OF SEISMOLOGY, AMERICAN GEOPHYSICAL UNION

The Meeting was called to order by the Vice-Chairman, Ralph R. Bodle, in the absence of the Chairman, A. J. Westland, S.J., who was still suffering from the effects of a serious accident. F. W. Sohon, S.J., Director of the Georgetown Seismic Station, welcomed the membership in the name of the President and Faculty of Georgetown University.

The minutes of the Fifteenth Annual Meeting were approved as published in the issue of Earthquake Notes of September, 1940. The Secretary reported that invitations for the next meeting had been received from Pennsylvania State College and the University of Pittsburgh.

J. B. Macelwane, S.J., Chairman of the Nominating Committee, submitted the Committee's selection of nominees for office for next year as follows: Chairman, R. R. Bodle, U. S. Coast and Geodetic Survey; Vice-Chairman, E. L. Perry, Williams College; Secretary, W. A. Lynch, Fordham University; Treasurer, H. Landsberg, Pennsylvania State College; fifth member of the Executive Committee, A. J. Westland, S.J., Spring Hill College. There were no nominations from the floor; the above were elected unanimously for the coming year.

The resignation of the Editor of Earthquake Notes, J. H. Nelson of the United States Coast and Geodetic Survey, was announced; his duties at his new post at Tucson, Arizona, forced him to take this action. Upon motion, the Secretary was instructed to extend to Mr. Nelson the thanks and appreciation of the Section for his fine work during the two years of his Editorship.

E. L. Perry reported for the Committee on Methods and Operations and distributed mimeographed copies of the report on the following topics: Master-clocks, types of recording paper, news items, and public education [see pp. 408-415].

H. Landsberg rendered his report as Treasurer; the report was accepted. He was authorized to continue on the subscribers' list of Earthquake Notes those in foreign countries who have had difficulty in making payment because of the international situation. A. Blake reported that the Auditing Committee had examined the Treasurer's report and found everything in order; the Committee commended the Treasurer for his work.

Upon motion, it was decided to make permanent the new Committees on Seismic Prospecting and on Engineering Seismology, respectively, that had been organized during the winter with D. Linehan, S.J., as Chairman of the former, and A. C. Ruge as Chairman of the latter; the Chairman of the Section was instructed to complete the membership of the Committees.

H. Landsberg reported that the Committee on Resolutions had drawn up resolutions to Father Westland with the hope for his speedy recovery, to Georgetown University with the thanks of the Section for the hospitality extended to it, and to the United States Navy and to the Dominion Observatory at Ottawa with appreciation of the time-signal service rendered by each. These resolutions were adopted and the Secretary was instructed to convey them to Father Westland and the officers involved.

The Vice-Chairman read a letter from J. E. Ramirez, S.J., on the new seismic vault at Bogota, Colombia, which is to be opened formally during the summer; Father Ramirez expressed the desire that the Section send a delegate to be present at the opening exercises; it was decided to do so if the matter can be arranged.

The Meeting was then turned over to the presentation of the papers and discussions of the formal program. As an added attraction to the program, B. Gutenberg presented the part of his paper on "Tectonic processes" given on May 1 before the Section of Tectonophysics of the American

Geophysical Union [see pp. 556-558] that was of particular interest to seismologists. The complete program as follows is printed in full or in abstract in these Transactions [pp. 397-415]:

(1) Rock-burst research at Lake Shore Mines, Kirkland Lake, Ontario, by E. A. Hodgson (read by title)
(2) Analysis of El Centro record of Imperial Valley Earthquake of 1940, by F. Neumann (read by R. R. Bodle)
(3) Amateur seismology, by J. Lynch, S.J.
(4) Discussion: Local earthquakes (originally scheduled as a discussion to have been led by L. D. Leet, this was changed to a report of the work of Northeastern Seismological Association on local earthquakes presented by D. Linehan, S.J.)
(5) The Moodus earthquakes and the cause of earthquakes in New England, by E. L. Perry
(6) Tectonic processes in action, by B. Gutenberg
(7) The New Hampshire earthquakes of December, 1940, by L. Don Leet, D. Linehan, S.J., L. C. Langguth, S.J., and J. J. Devlin, S.J.
(8) Travel-time tables for near earthquakes in east-central North America, by E. J. Walter and H. F. Birkenhauer, S.J. (read by title; mimeographed copies of the tables were distributed by V. C. Stechschulte, S.J.)
(9) Surface-waves in heterogeneous media, by J. T. Wilson
(10) Trials of galvanometers of various periods with electromagnetic seismometers, by W. A. Lynch
(11) Discussion: Earthquake-records at epicentral distances of about twenty degrees, led by D. Linehan, S.J.
(12) Progress-report on periodicity and time-series, by Archie Blake

The Meeting adjourned at 1 p.m. The members were then escorted by F. W. Sohon, S.J., to the dining hall of the University where an excellent luncheon was served; we were all happy to rise to voice our thanks to Father Sohon and to Georgetown University for the care and thoroughness of the arrangements for our entertainment.

W. A. Lynch, Secretary,
Eastern Section,
Seismological Society of America

APPENDIX E-c--MINUTES OF THE ANNUAL MEETING OF 1941, SECTION OF METEOROLOGY, AMERICAN GEOPHYSICAL UNION

The Twenty-Second Annual Meeting of the Section of Meteorology, Vice-President Thornthwaite presiding in place of President Weightman who was absent in South America on official business, was held from 9:15 a.m. to 12:05 p.m., May 1, 1941, in the Lecture Room of the National Academy and Research Council Building, Washington, D. C. About 100 members and guests registered their attendance [see Appendix A].

The reading of the minutes of the previous Meeting was dispensed with as they had already been published in the Transactions of 1940 and no corrections or additions had been received.

The Secretary announced that Part II (Memoirs and discussions) of the Transactions of the International Association of Meteorology, Washington Meeting, September 1939, had been published in Bergen, Norway, but that as yet only a small number of copies had reached this country.

The Nominating Committee [I. R. Tannehill (Chairman), H. R. Byers, and O. H. Gish] nominated for officers for the three-year period beginning July 1, 1941, C. W. Thornthwaite for President, C.-G. Rossby for Vice-President, and H. D. Harradon for Secretary. No other nominations were made and these candidates were duly elected.

The Committee on Resolutions (P. E. Church and E. W. Woolard) presented a resolution regarding cooperation of the various meteorological institutions for providing a more adequate bibliographic service which was accepted by the Section and referred to the Committee on Resolutions of the Union [see p. 563].

There being no further business, the scientific program was presented including the papers printed in these Transactions [pp. 419-437].

H. D. Harradon, Secretary,
Section of Meteorology,
American Geophysical Union

APPENDIX E-d--MINUTES OF THE ANNUAL MEETING OF 1941, SECTION OF TERRESTRIAL MAGNETISM AND ELECTRICITY, AMERICAN GEOPHYSICAL UNION

The Twenty-Second Annual Meeting of the Section of Terrestrial Magnetism and Electricity was called to order by President E. O. Hulburt at 9:12 a.m., April 30, 1941, in Room B of the Departmental Auditorium in Washington, D. C. The registered attendance was 66 [see Appendix A].

The minutes of the Twenty-First Annual Meeting had been published in the Transactions of 1940, and since no corrections or additions had been received, they were declared approved as printed.

The Nominating Committee [H. E. McComb (Chairman), O. H. Gish, L. V. Berkner, T. H. Johnson, and O. R. Wulf] presented the following nominees for the offices of President, Vice-President, and Secretary of the Section of Terrestrial Magnetism and Electricity for the three-year period beginning July 1, 1941: For President, E. A. Eckhardt; for Vice-President, H. F. Johnston; for Secretary, J. W. Joyce.

A motion was made and seconded that the report of the Nominating Committee be accepted. The motion was carried. It was then moved and seconded that the nominations be closed and that the Secretary be instructed to cast a unanimous ballot for the candidates. The motion was carried.

There being no further business, the Section proceeded to the scientific program and the papers published in these Transactions were presented [pp. 441-470]. The last four papers were read by title only.

At the conclusion of the presentation of papers, the following motion was presented by Dr. H. H. Howe:

> That a Committee on Units be appointed for the purpose of consulting with similar committees of other organizations, and with other authorities, regarding the names and magnitudes that should be used for units used in the fields of geomagnetism and geoelectricity. The Committee is to consist of five members, and be appointed for one year. It is to submit to the next meeting specific recommendations for standardizing usage.

The motion was duly seconded and carried. No further action was taken at the time of the Meeting.

The Meeting was adjourned at 11:55 a.m.

J. W. Joyce, Secretary,
Section of Terrestrial Magnetism
and Electricity,
American Geophysical Union

APPENDIX E-e--MINUTES OF THE ANNUAL MEETING OF 1941, SECTION OF OCEANOGRAPHY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Oceanography was held at Washington, D. C., Friday, May 2, 1941, in the Library of the National Academy and Research Council Building, Washington, D. C. The Meeting was called to order by President C. O'D. Iselin at 9:00 a.m. There were 100 members and guests present [see Appendix A].

The report of the Nominating Committee was read by the Acting Secretary and a motion was made by Dr. T. Wayland Vaughan to instruct the Secretary to cast a unanimous vote for the nominees, namely, Paul C. Whitney, President, H. R. Sverdrup, Vice-President, and Waldo L. Schmitt, Secretary.

There being no new business and no reports of special or standing committees, the papers scheduled for this Section were heard as published in these Transactions [pp. 473-498].

Colbert's paper was discussed by T. Wayland Vaughan and others. Spilhaus' paper was discussed by Sverdrup, Smith, and others. Church's paper was discussed by Thornthwaite. Sverdrup's paper was discussed by Vaughan, Woodring, Arctowski, Smith, and others. President Iselin gave an informal report on the recent acquisition by the Woods Hole Oceanographic Institution of the new vessel Anton Dohrn.

The Meeting was adjourned at 11:30 a.m.

Paul A. Smith, Acting Secretary,
Section of Oceanography,
American Geophysical Union

APPENDIX E-f--MINUTES OF THE ANNUAL MEETING OF 1941, SECTION OF VOLCANOLOGY, AMERICAN GEOPHYSICAL UNION

The Annual Meeting of the Section of Volcanology was held in Room A, Departmental Auditorium, between 12th and 14th Streets on Constitution Avenue, Washington, D. C., April 30, 1941. The morning session was called to order at 9:15 a.m. by President E. G. Zies, with a registered attendance of 34 [see Appendix A]. The report of the Nominating Committee was read by Chairman A. H. Koschmann, and was accepted by vote of the Section. Acceptance of the report meant the election of the following officers for the term 1941-1944: President, A. F. Buddington; Vice-President, J. F. Schairer; Secretary, J. S. Vhay.

The reading of the minutes of the previous Annual Meeting was dispensed with.

The brief business meeting was followed by presentation of the scientific papers as published in these Transactions [pp. 501-516].

The paper by Keevil was read by title, that by Gibson was discussed by Graton and that by Ingerson and Morey by Graton, Gibson, Lovering, Larsen, Greig, Adams, Kracek, Fleischer, and Morey. The papers by J. S. Griffith on "The system wollastonite-albite-anorthite" and by W. K. Gummer on "The system wollastonite-anorthite-nepheline," of which no manuscripts or abstracts were received, were read by title. The first paper by Nichols was discussed by Morey, Graton, and Lane, and his second paper by Marble, Graton, Lane, Ross, and Larsen. The last paper of the program by Keppel was discussed by Lane, Ingerson, and Graton.

The morning session adjourned at 11:50 a.m.

The afternoon session, President Zies presiding, with a registered attendance of 46 [see Appendix A], was called to order at 2:20 p.m. and papers were presented as published in these Transactions [pp. 501-516].

Discussion of the papers was as follows: Paper by Chayes by Shand, Marble, Koschmann, Graton, and Larsen; paper by Fraser by Lane; paper by McNish by Lane, Gutenberg, Field, and Greig; paper by Wright by Greig, Larsen, Graton, and Gutenberg; paper by Zies by Koschmann, Graton, and Tunell.

Earl Ingerson, Secretary,
Section of Volcanology,
American Geophysical Union

APPENDIX E-g--MINUTES OF THE ANNUAL MEETING OF 1941, SECTION OF HYDROLOGY, AMERICAN GEOPHYSICAL UNION

The Section of Hydrology held three sessions in the National Academy and Research Council Building on May 1 and 2, and a round-table discussion in the North Building, Department of the Interior, on May 3, 1941.

The first session was called to order at 9:05 a.m., May 1, in the Auditorium by President Grover. Ten papers and five reports of Research Committees were presented. Seventy-eight members and guests registered attendance [see Appendix A]. The session adjourned at 11:46 a.m.

The second session was called to order at 2 p.m., May 1, in the Auditorium by President Grover. The minutes of the Annual Meeting of 1940, as published in the Transactions of 1940 [p. 748], were approved. The following motions were carried unanimously:

(1) That the members of the Section of Hydrology, American Geophysical Union, send greetings to Harry R. Leach, member of the Executive Committee of the Section, with regrets that he is unable to meet with them and with their best wishes for his early return to health.
(2) That the Northeastern Snow-Survey Conference and the Great Lakes Snow-Survey Conference

be granted provision for cooperation with the Section of Hydrology, American Geophysical Union, in the same manner and under the same conditions that cooperation has been extended to the Western Interstate Snow-Survey Conference heretofore. (In particular, these Conferences shall pay full costs of any of their publications, and acceptance of such publications shall be subject to the approval of the Editorial Committee of the Section of Hydrology and of the General Secretary of the American Geophysical Union.

Sixteen papers and the reports of five Research Committees were presented. Eighty-two members and guests registered attendance [see Appendix A]. The session adjourned at 5:30 p.m.

The third session was called to order at 9:05 a.m., May 2, in the Auditorium by President Grover. Fourteen papers and the reports of four Research Committees were presented. Sixty-seven members and guests registered attendance [see Appendix A]. The session adjourned at 11:58 a.m.

The round-table conference was called to order at 9:00 a.m., May 3, in Room 5243 of the Department of the Interior by the leader, W. G. Hoyt. The subjects of runoff and infiltration, and their correlation, were discussed until the middle of the afternoon with an intermission for lunch. About one hundred members and guests were present.

The total registration of members and guests at the regular sessions and the round-table conference was 158 [see Appendix A].

The papers and discussions, and reports of the Research Committees are published in these Transactions [see Part III].

K. Hilding Beij, Secretary,
Section of Hydrology,
American Geophysical Union

APPENDIX E-h--MINUTES OF THE ANNUAL MEETING OF 1941, SECTION OF TECTONOPHYSICS, AMERICAN GEOPHYSICAL UNION

The Second Annual Meeting of the Section of Tectonophysics consisted of two scientific sessions in the morning and afternoon of May 1, 1941, with President L. H. Adams presiding. There being no business to be considered, the presentation of the scientific papers published in these Transactions [pp. 519-558] was proceeded with at once. Under the guidance of our sympathetic President, the sessions were kept moving at a rapid tempo until 6:30 p.m. The total registered attendance of members and guests at the two sessions was 79 [see Appendix A].

David Griggs, Secretary,
Section of Tectonophysics,
American Geophysical Union

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